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IN ENGLISH TRANSLATION

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SIGNIFICANCE OF ABBREVIATIONS MOST FREQUENTLY ENCOUNTERED IN SOVIET PHYSICS PERIODICALS

AN SSSR	*Academy of Sciences, USSR*
FIAN	*Physics Institute, Academy of Sciences USSR*
GITI	*State Scientific and Technical Press*
GITTL	*State Press for Technical and Theoretical Literature*
GOI	*State Optical Institute*
GONTI	*State United Scientific and Technical Press*
Gosenergoizdat	*State Power Press*
Gosfizkhimizdat	*State Physical Chemistry Press*
Gozkhimizdat	*State Chemistry Press*
GOST	*All-Union State Standard*
Goztekhizdat	*State Technical Press*
GTTI	*State Technical and Theoretical Press*
GUPIAE	*State Office for Utilization of Atomic Energy*
IF KhI	*Institute of Physical Chemistry Research*
IFP	*Institute of Physical Problems*
IL	*Foreign Literature Press*
IPF	*Institute of Applied Physics*
IPM	*Institute of Applied Mathematics*
IREA	*Institute of Chemical Reagents*
ISN (Izd. Sov. Nauk)	*Soviet Science Press*
I YaP	*Institute of Nuclear Studies*
Izd	*Press (publishing house)*
KISO	*Solar Research Commission*
LETI	*Leningrad Electrotechnical Institute*
LFTI	*Leningrad Institute of Physics and Technology*
LIM	*Leningrad Institute of Metals*
LITMiO	*Leningrad Institute of Precision Instruments and Optics*
Mashgiz	*State Scientific-Technical Press for Machine Construction Literature*
MATI	*Moscow Aviation Technology Institute*
MGU	*Moscow State University*
Metallurgizdat	*Metallurgy Press*
MOPI	*Moscow Regional Institute of Physics*
NIAFIZ	*Scientific Research Association for Physics*
NIFI	*Scientific Research Institute of Physics*
NIIMM	*Scientific Research Institute of Mathematics and Mechanics*
NII ZVUKSZAPIOI	*Scientific Research Institute of Sound Recording*
NIKFI	*Scientific Institute of Motion Picture Photography*
OIYaI	*Joint Institute of Nuclear Studies*
ONTI	*United Scientific and Technical Press*
OTI	*Division of Technical Information*
OTN	*Division of Technical Science*
RIAN	*Radium Institute, Academy of Sciences of the USSR*
SPB	*All-Union Special Planning Office*
Stroiizdat	*Construction Press*
URALFTI	*Ural Institute of Physics and Technology*

NOTE: Abbreviations not on this list and not explained in the translation have been transliterated, no further information about their significance being available to us.—*Publisher.*

A GREAT DATE

The Soviet nation and all the progressive peoples of the world are now celebrating the fortieth anniversary of the Great October Socialist Revolution. For forty years the Soviet people under the leadership of the glorious Communist Party have been building a society whose principal aim it is "to ensure the complete well-being and full free development of all of its members" (Lenin).

Now all can see what an unsurpassably progressive beginning has been made toward socialism. The facts of the past forty-year period speak eloquently of this. Prerevolutionary Russia was economically a backward and semi-colonial country. In 1913 the total industrial production of Russia was 4.5 times less than that of England, 5.9 times less than that of Germany and 14.5 times less than that of the USA. During the years of Soviet rule, of which not less than 18 were spent in the Civil War and the Second World War into which the Soviet Government was forced, and in the restoration of the national economy which had been destroyed by these wars, the total industrial production of our country was increased more than 30 times, so that it is now second in the world. History knows no other such rapidity of industrial development. Even the most highly developed capitalistic countries required 10 times longer to achieve similar results.

The achievements of Soviet agriculture are also great. We may confine ourselves to only one representative figure: while the prerevolutionary production of grain in Russia was 1300 million poods (1 pood equals 36 pounds), in 1956 the collective and state farms delivered or sold to the government 3304 million poods.

The Soviet people have also had remarkable success in the development of culture and science. In the training of specialists the Soviet Union has by now considerably surpassed the leading capitalistic countries. During the years of Soviet rule the higher institutions of learning alone have graduated more than 3.5 million specialists, including about one million engineers. About three thousand research institutes, laboratories and other scientific organizations are working on the most varied problems of science and technology. Under the conditions of Soviet construction there has grown up a corps of many first-class scientists recognized all over the world.

The Soviet Government places great stress on the development of science and on putting into practice the results of scientific developments; both the industry and agriculture of the country have their basis in scientific achievements. The outstanding achievements of Soviet scientists in mathematics, mechanics, physics, chemistry and electronics have brought the solutions of highly complex problems in the development of power, machine construction, metallurgy, radio, automation and remote control; we have been able to introduce the newest techniques into production and to develop highly efficient technological processes. The scientists of the Soviet Union are highly regarded, respected and cared for. Is it therefore surprising that the Soviet nation has become the pioneer in the extensive utilization of atomic energy for peaceful purposes and is the home of the first atomic power plant?

The Soviet Union has built the most powerful particle accelerator in the world, the proton synchrotron, which will accelerate protons to 10 billion electron volts.

An outstanding achievement of Soviet scientists and engineers has been the production of intercontinental ballistic missiles and of the means of launching them.

A real triumph of Soviet science and technology was the construction and launching of the earth's first artificial satellite. In this way Soviet science opened a new era of world science and has made a decisive step forward on the path toward the conquering of interplanetary space.

In forty years the previously backward Russia has been transformed into a mighty industrial power with the greatest agricultural production in the world. The economic and political victories of the Soviet nation are so re-

markable that we now possess all of the means for fulfilling the historical task set by the 20th Congress of the Communist Party of the Soviet Union. "The Congress regards it as absolutely necessary to continue with all urgency the endeavor to accomplish, by means of peaceful economic rivalry and in the shortest possible time, the principal economic task of the Soviet Union, which is, based on the preeminence of the socialist economic system, to overtake and surpass the most highly developed capitalistic countries in the production of consumers' goods."

Its entire history of forty years has led our country toward the successful attainment of this goal. The country which has been victorious in two wars and has overcome the terrible damage to its economy which resulted from those wars is now fully prepared to reach this principal economic goal.

Socialism is a synonym of peace. In a socialist society there are no classes which are interested in war. It does not contain the antagonism and contradictions which are characteristic of capitalism and which bourgeois society seeks to resolve by war. With the founding of the first socialist government a new epoch in international relations began, based on Lenin's principle of the peaceful coexistence of the capitalistic and socialistic systems. The principle of peaceful coexistence means not only that there will be no war between the two systems, but also that there will be peaceful economic rivalry between them, and constructive cooperation in economic, political and cultural fields, especially the expansion of trade, joint assistance to underdeveloped countries for their industrialization, joint projects for the transformation of nature, etc.

The Soviet peoples look back with satisfaction on the path which they have followed. As for all pioneers, the path was not an easy one, but they have confidently moved forward toward communism. Only forty years ago, the most vulnerable link in the capitalist chain was broken and now a socialistic system exists which comprises 35% of the world's population, 25% of its territory and about 30% of its industrial production. Now the peoples of many countries are moving steadfastly along with the Soviet people towards the heights where the beautiful sun of the future shines. No one can ever halt this great forward movement.

DEVELOPMENT OF ATOMIC POWER IN THE SOVIET UNION

N.A. Nikolaev

The power requirements of the Soviet Union can, in general, be fully satisfied by the tremendous reserves of organic fuel and usable hydroelectric resources of the country.

However, at the present time about 80% of the generated electrical energy and the fuel produced throughout the country are used in the European part of the USSR and in the Urals. Although in the coming years the share of the eastern sections of the country in the energy balance of the nation will grow substantially, nevertheless, even in the year 1975 the European part of the USSR and the Urals will use two-thirds of the energy generated in the nation.

The satisfaction of the energy requirements of European Russia and the Urals from the Donets and Pechora coal basins is becoming a difficult and expensive proposition while delivery of fuel from the eastern sections of the USSR is not economically justifiable. For this reason it is already economically sound to use atomic energy in these regions. The feasibility of adopting atomic energy to industrial uses was first proven in the Soviet Union on June 27, 1954, by the operation of an atomic electric station of 5 Mw capacity.

For over three years the station has been operating reliably without interruption and has turned out to be simple, convenient and safe to operate, all its equipment having successfully passed lengthy tests.

The construction of this power station is the first step in the development of power generation from atomic energy in the USSR. At the present time, the problems before us are the improvement and perfection of the designs of atomic power stations, the creation of new types of stations, the elevation of their power capacities and the improvement of economic performance.

In accordance with the sixth five-year plan there will be built in our country atomic power stations of total power capacity of $(2\text{-}2.5)\cdot 10^3$ Mw. The program calls for the construction of powerful atomic power stations (400 to 600 Mw each), as well as the erection of experimental stations of low power capacity including various types of reactors. The atomic power stations will aim at the simultaneous generation of electrical energy for satisfaction of the needs of the economy as well as the study of the operation of large generating stations and the determination of their costs.

It seems apparent that economically satisfactory operation of atomic energy can be attained only in large atomic power stations, whose capacity is comparable to that of the very large electro-generating stations that operate on organic fuel. The economy of large atomic stations is determined not only by ordinary factors but by specific peculiarities of atomic stations; for instance, large atomic power stations with large reactors can utilize a fuel of lower enrichment, produce more nearly complete fuel burnup, etc. The new atomic stations will be equipped with reactors whose working principles have been well studied and whose use appears to be most feasible at the present time. The power capacity of each of these reactors will be about 100 to 200 Mw.

Within the current five-year period there will be erected powerful atomic power stations with three types of reactors. The first type will be analogous to the atomic power station now operating in the USSR.*

This station will use modern turbines rated at 100 Mw each, and designed for high steam parameters (90 at-

*A description of this station, its basic layout and basic parameters are given in the article by N.A. Dollezhal[1] (see page 1249)

mos a. pressure, 500°C superheated steam temperature). Since superheating of the steam takes place in the reactor in this station, there is no need for a superheater, which is usually the most costly element of steam generation. The steam generator supplies steam of insignificant salt content (not over 0.05 mg/kg), which in passing through the reactor within 0.3 sec is lightly activated (essentially only an insignificant oxygen activity arises) and therefore there is no need for special biological shielding around the turbine and the steam ducts.

Due to the high-steam parameters the efficiency of this atomic power station is quite high – over 35%. By comparison, efficiencies of this type are shown only by modern large coal-burning power stations that operate on high- and ultra-high steam parameters.

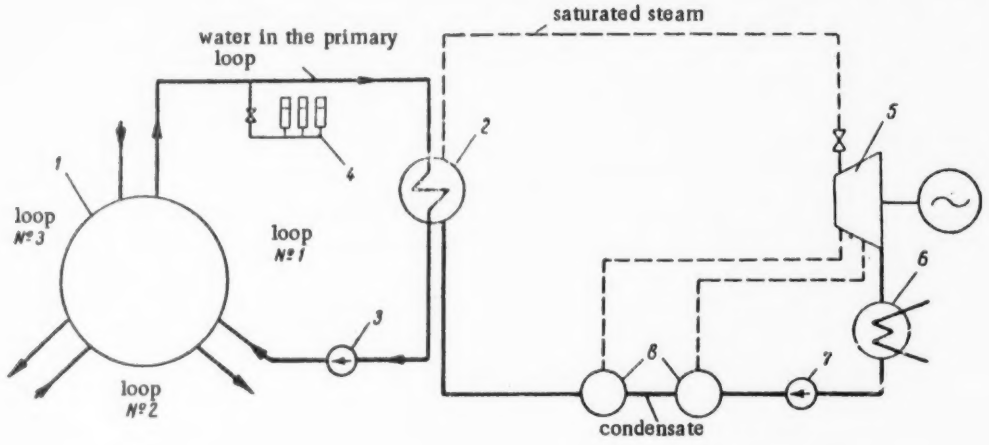

Fig. 1. Schematic diagram of one unit of an atomic power station with water cooled and moderated reactor enclosed in a pressure shell: 1) reactor; 2) steam generator; 3) circulating pump of the primary loop; 4) expansion chambers; 5) turbo-generator; 6) condenser; 7) feed pump for secondary loop water; 8) regenerative preheaters.

The second type of atomic power station will be equipped with pressurized water, thermal neutron reactors, that is, common water will be used for both moderator and coolant in the reactors. This station will use a two loop layout for removing the heat (Figure 1). The schematic diagram shows the steam generating installation of one unit of the station. Each unit has an electrical power capacity of 210 Mw and consists of one reactor and three steam generating loops with steam generators, circulating pumps for the primary loop and three turbo-generators of 70 Mw each. Water from the reactor at a pressure of 100 atmos a. and at a temperature of 275°C enters the steam generators at a rate of about 10,000 m^3/hr, transfers its heat to the water of the secondary loop, is thereby cooled to a temperature of 250°C, and is then pumped again to the reactor.

If necessary, each loop may be shut off from the reactor through two connectors; then the reactor and the whole station can operate at a correspondingly lower power level. A primary loop layout of this type improves the reliability of the station and allows maintenance and inspection of the basic equipment of these loops to be performed without shutting down the station and the reactor.

The feed pumps of the secondary loop supply water to the steam generators through the regenerative preheaters. Saturated steam at 30 atmos a. leaves the steam generators and enters the turbines.

The turbines, developed at the Khar'kov turbogenerator plant, utilize intermediate steam separation, thus ensuring that the allowable steam moisture, not over 12%, will reach the blades of the final pressure stage of the turbine.

The nuclear fuel in the reactor is low enrichment uranium (UO_2) enclosed in a cladding of zirconium alloy.

Advantages of this type of station are the possibility of high uranium burnup and the relatively simple design of the reactor installation. It is assumed that the cost of electrical energy will be comparable to the cost of electricity generated by the best thermal power stations.

There is great interest in the third type of atomic power station which has a thermal neutron reactor in which heavy water is used as the moderator, and the coolant is carbon dioxide that is circulated under a pressure of 60-70 atmos a. through a closed loop.

The carbon dioxide gas, heated to a temperature of 500°C in the reactor, enters the steam generator, where it transfers heat to the water of the secondary loop, and then is blown back into the reactor. The water of the secondary loop is fed to the steam generator, where it becomes superheated steam at a pressure of 30 atmos a. and a temperature of 400°C, and is then directed through a standard turbine of medium pressure and power rating of 50-100 Mw.

In connection with the use of heavy water for moderator, natural uranium, which costs considerably less than enriched uranium, may be used in the reactor. In this lies the advantage of a station of this type.

The installation of powerful atomic power stations will improve basically the energy supply of those regions where they are to be built. At the same time, their installation will allow the study of the peculiarities of long term exploitation of large atomic power stations, make possible the determination of the advantages and disadvantages of each type of station, and allow the accumulation of necessary experience and exhaustive data for the future design and erection of more effective and more economical atomic power stations.

In addition to the stations described above, during the sixth five-year plan four experimental power installations are to be built of lower power capacity with reactors that are apparently promising but need to be studied thoroughly.

It is proposed to include,in one of these installations of 70 Mw electrical power,a thermal neutron boiling water reactor using common water as both moderator and coolant. Steam generated in the reactor will go directly to the turbine.

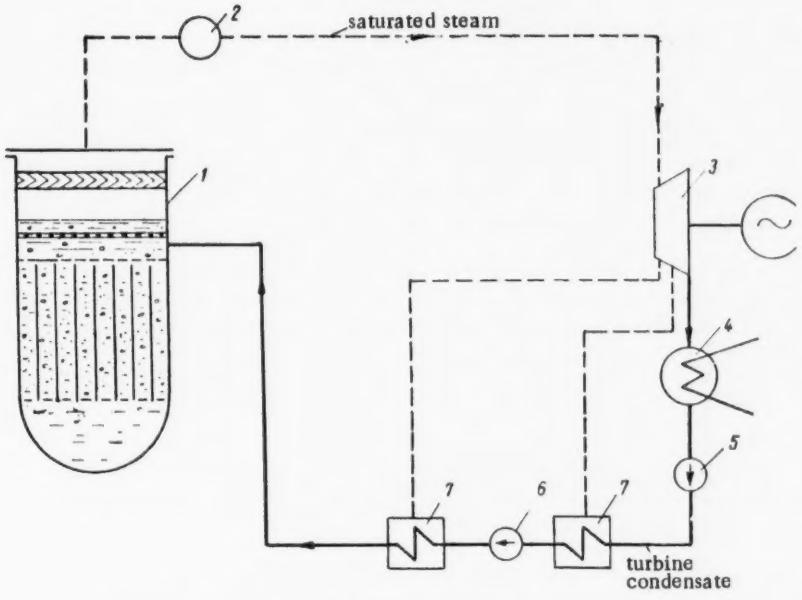

Fig. 2. Essential schematic layout of an atomic power station with boiling-water reactor: 1) reactor; 2) steam separator; 3) turbogenerator; 4) condenser; 5) condensate pump; 6) feed pump; 7) regenerative preheaters.

Figure 2 shows the principal schematic diagram of this station. Saturated steam at 29 atmos a. is fed to the turbine 3. Since this steam is radioactive, the turbine will probably require biological shielding around it and also will require remote control. It is proposed to study the stability of operation and control characteristics of the boiling-water reactor. It is also necessary to study the operational peculiarities of the turbine when working with radioactive steam.

The use of a single-loop scheme is very attractive and feasible since the layout of the station is significantly simplified and the use of steam generators, which involve considerable cost, is eliminated.

The second experimental station of 50 Mw electrical power will use a thermal neutron reactor with graphite moderator and molten sodium as the coolant.

The essential layout of the station includes the reactor cooled by four primary sodium loops with intermediate heat exchangers and pumps, two secondary sodium loops with steam generators and pumps, and a turbogenerator with condenser and feed water pumps.

The use of sodium allows the attainment of high temperatures without the necessity of high pressures in the loop and produces steam of high parameters, which ensures a substantial efficiency.

The use of a three-loop scheme for removing heat from the reactor is essential at the present time, since a rupture of tubing in the water-sodium heat exchangers could lead to an energetic reaction between the water and the radioactive sodium with production and expulsion of highly radioactive steam; in addition the use of an intermediate nonradioactive loop simplifies the maintenance of steam generators.

The sodium at exit from the reactor is at 560°C, thus allowing coolant temperatures in the secondary loop of 540°C which produces superheated steam at a temperature of 500°C at a pressure of 90 atmos a.

The reactor is in the form of a cylindrical graphite pile penetrated by vertical openings into which the fuel elements containing slightly enriched uranium and clad with stainless steel, are inserted. The choice of graphite for moderator was essentially dictated by its weak reaction with sodium, and also by the ease of operation and the low cost of the graphite in comparison with other moderators. The operation of this station will allow the accumulation of needed experience in maintaining reactor installations involving sodium coolants, and will determine the feasibility of a more powerful station using reactors of this type.

The third experimental station will include a homogeneous boiling-water reactor with natural circulation.

The fuel will be a fine power or solution of uranium salts in heavy water. The reactor is intended for production of fuel through the Th^{232}-U^{233} cycle. The heat is removed from the reactor through a dual loop arrangement.

The heavy water of the primary loop is heated to a boil in the reactor and enters the steam generator in the form of saturated steam, where it transfers heat to the water of the secondary loop and returns to the core of the reactor to be reheated to boiling. The feed water of the second loop enters the steam generator where it is heated, vaporizes and superheats, and thereafter is led to the turbine.

Homogeneous reactors may be of high power capacity under comparatively small nuclear fuel investments. One of their advantages is also the possibility of uninterrupted separation of fission products from the nuclear fuel. The above-indicated advantages, as well as the absence of structural materials within the core, which improves the neutron economy of the reactor, attracts great interest.

The above reactors using thermal neutrons do not solve the problems of complete utilization of natural uranium.

From this standpoint, fast reactors appear desirable. They are not so sensitive to the composition of structural materials in the core as thermal reactors, since with increasing energy, capture cross sections decrease and the neutron economy of the reactor is improved.

In fast neutron reactors it is possible to obtain a high power density (or specific power), on the order of 1 Mw per 1 liter of core, which requires the creation of a particularly effective system of heat removal.

Breeding coefficients of 1.5 and even higher can be attained in fast neutron reactors.

Therefore, in order to accumulate operating experience with fast neutron powers and to check their cost characteristics, a fourth experimental power installation including a fast neutron reactor and improved breeding is being assembled.

Fuel in the core will be plutonium, and in the breeding zone, U^{238}. It is evident from Figure 3 that heat removal will be through a three-loop arrangement.

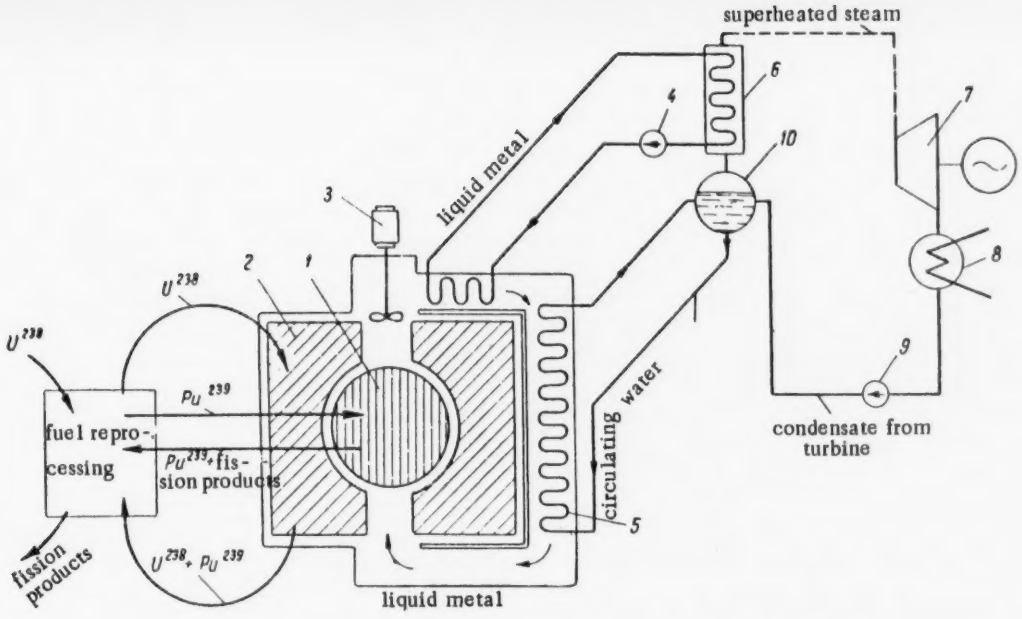

Fig. 3. Essential schematic diagram of an atomic power station with a fast neutron reactor: 1) reactor core; 2) U^{238} breeding region; 3, 4) pumps for liquid metal coolant; 5) steam generator (vaporizer); 6) steam superheater; 7) turbo-generator; 8) condenser; 9) condensate pump; 10) steam separator.

The coolant is liquid sodium at a temperature of 480°C at the reactor exit. An alloy of sodium and potassium or sodium alone is used in the secondary loop. Steam from the steam generators at a temperature of 420°C and a pressure of 32 atmos a. enters a standard steam turbine.

Each of the reactor types listed here has its own advantages and disadvantages. Features of a particular type of reactor are determined principally by the moderator and the coolant.

It is difficult to decide which of these reactors should receive preference, and it is doubtful that this selection can be made in the near future. Therefore, it seems desirable to conduct studies of all the basic types of power reactors, at least for some time, and this should be carried out regardless of the apparent advantages, at this time, of a particular type.

The operation of the large power and experimental atomic stations being built during this five-year plan will allow the accumulation of cost data on the electrical energy produced and will make possible comparison of the capital costs of construction which are difficult to predict accurately merely on the basis of design estimates.

The most important economic characteristics of atomic power stations are the capital investment required per 1 kw of installed power and the cost of fuel per one kw-hr of generated electrical energy. The table shows basic economic characteristics as designed into three types of large atomic power stations now under construction. These characteristics are approximate, since in many of the cases they are based on estimated figures.

Because of the lack of experience in fabrication of nonstandard equipment it is at present difficult to determine accurately the fabrication costs of several loops and components of atomic power stations. For evaluation of the economic characteristics of the stations under construction, current prices of materials and equipment were used. As supplies increase, the cost of materials used in reactor building will decrease. Similarly, as mass production technology is mastered, the cost of preparation and of chemical reprocessing of fuel elements will also decrease significantly.

To reduce the cost of generated electrical energy through a reduction in unit fuel cost it is essential to obtain greater fuel burnup through a lengthening of the operating run, whose duration depends on endurance of the

Characteristic	Coal-burning power stations	Atomic power stations		
		1	2	3
Electrical power, Mw	400	400	420	300
Efficiency (over-all) %	30	35.6	27.6	21.4
Reactor type	–	Moderator-graphite, coolant-water and steam under pressure	Moderator and coolant – water under pressure	Moderator – heavy water, coolant – carbon dioxide gas
Fuel	Coal	Low enrichment uranium	Low enrichment uranium	Natural uranium
Capital investment per one kw installed power, %	100	150	125	200
Total cost per one kw-hr,%	100	100	80	125
Unit fuel cost of electrical energy	100	90	60	50

fuel elements and their structural materials. For this reason the development of good design for fuel elements assumes great significance.

It can be assumed that the cost of electrical energy generated at large atomic power stations will be lower than at coal-burning stations.

The construction and operation of the various types of atomic power stations described here will allow the selection of the subsequent desirable course of development of atomic energy for power generation in our country.

URANIUM-GRAPHITE REACTORS FOR POWER STATIONS USING SUPERHEATED STEAM

N.A. Dollezhal

Over three years have passed since the day of initial operation of the first Soviet atomic power station. The successful operation of the station has demonstrated that there are no technical barriers to the utilization of atomic energy for electrical power generation, and that the tremendous quantities of fissionable materials collecting in various countries can be put to peaceful uses. The announcements over the past three years of a large number of atomic power-station projects confirm this basic conclusion, and the current pressing question is concerned with the cost of generated electrical energy and with the choice of the most economical type of nuclear reactor.

Since at the present time there is no thoroughly worked out system of technical indicators upon which the design and construction of atomic power stations could be based, it appears necessary that some time be devoted to the operational testing of the various engineering decisions. Some of these decisions will be found lacking, others will be sustained and their further development will be justified. In other words, it can be asserted that the principal questions concerned with the development of atomic energy in most cases will be decided on the basis of designs of power reactors whose erection will produce the greatest effect on the national economy. The effectiveness of a design for an atomic power station, in general, can be determined through the following relationship*:

$$m \approx k \frac{Na}{\frac{B_{in} - B_{fin}}{T}}, \qquad (1)$$

where N is the power rating of the station (for instance, in Mw), equal to the product of the thermal power of the reactor Q_{th} (also in Mw) and the thermal efficiency of the station, η_{net} ($N = Q_{th} \times \eta_{net}$); $\underline{a}$ is the maximum cost of a unit of electrical energy (for instance, of 1 Mw-hr), generated by the atomic power station; B_{in} is the cost of the initial uranium loading in the reactor, of corrosion and fracture resistant cladding of the fuel elements, and of various structural details (that are replaced in the reactor simultaneously with uranium replacement); B_{fin} is the cost of fuel elements removed from the reactor after completion of their term of operation; T is the duration of a run, that is, the time in hours or days, during which the fission process takes place in the fuel elements; $\underline{k}$ is the coefficient that takes into account certain basic features of an atomic power station, for instance for comparison with coal-burning power stations.

The value of the cost B_{in} can be represented as the sum of three basic parts: 1) the product of the weight g of uranium and the cost of the uranium, b_1, enriched with U^{235} to a value of x_1% (the value x_1 is determined during the designing of the reactor and depends on its type and operating conditions; 2) the cost C_1 of fabrication of fuel elements from uranium with the selected enrichment; and 3) the cost, C_2, of structural elements (enclosure, supports, and so on), that are necessary for the location of the fuel elements in the reactor and for their re-

*The product "Na" is the "income" portion of the exploitation cost estimates for the power station; therefore, in examining the question of best design of an atomic station, designated not only for generation of electrical energy, but for supplying heat as well, besides the cost of the electrical energy the cost of the delivered heat should be introduced into the numerator.

moval and replacement.

The cost B_{fin} is determined first, by the cost of the remaining U^{235} represented by the quantity $x_2\%$, of the plutonium represented by the quantity y%, which was formed in the reactor, is fissionable, and therefore of value; and by the cost of certain structural details which can be used for a second time. Secondly, the quantity B_{fin} is influenced by the costs involved in reprocessing of fuel elements for extraction from them of uranium and plutonium.

Thus, the quantity B_{fin} can be represented in the form of a sum of the following basic parts: 1) the product of the weight g of unloaded uranium and the cost of uranium b_2 containing $x_2\%$ U^{235}; 2) the product of the weight of plutonium ($q \approx yg/100$) and the established price of plutonium, b_3; 3) the cost of the returnable parts C_3 which form part of the cost C_2 of fabricating new fuel elements; 4) by the cost C_4 of reprocessing of used fuel elements for the purpose of extraction of uranium and plutonium.

The quantity, B_{fin}, is determined by the difference between the sum of the first three terms and the fourth term. The lower the value of the fourth term, that is, the more economical the reprocessing of the used fuel elements, the greater, other conditions being equal, the value of B_{fin}.

The quantity, T, is established during design of the reactor and is directly connected to the loading and the degree of enrichment of uranium with isotope U^{235}. In principle, the higher the enrichment, the longer the length of the operating run. However, T is affected most by the corrosion resistance of the materials of construction of the fuel elements and by their resistance to radiation damage and other effects.

The coefficient k characterizes in part, the relative increase in capital costs incurred in construction of the atomic station, the maintenance costs and a series of other cost indicators. In some cases the coefficient k may be greater or smaller than unity.

Therefore, in order to have the erection of an atomic power station more effective than that of a coal-burning station, it is essential that the dimensionless parameter m be greater than unity. The greater the value of m, the more effective is the atomic power station, and the more advantageous is its erection.

Equation (1) may be written in the following form:

$$m \approx ka \frac{W\eta_{net}}{(b_1 - b_2) - R\frac{x_1 - x_2}{100} b_3 + \frac{C_1}{g} + \frac{C_2 - C_3}{g} + \frac{C_4}{g}}. \qquad (2)$$

Here W is the quantity of thermal energy (Mw-days) that is produced by each ton of uranium that is loaded in the reactor; R is the breeding coefficient of the nuclear fuel, that is, the number of atoms of plutonium formed during the operating run, over the number of atoms of U^{235} fissioned during the operating run.

Analysis of the parameter m as defined by Equation (2) leads to supplementary basic conclusions. For instance, it is possible to assert that the greater the value of W, the lower the relative cost of electrical energy generated by the atomic power station. An illustration of this is the curve shown in Figure 1. This curve, calculated for the atomic power station "Calder Hall" (England), characterizes the cost of electrical energy as a function of the quantity of fissioned U^{235} per one ton of uranium loading, that is, as a function of the quantity W.

Analogous curves calculated for other reactors show that an optimum value of W exists, when the cost of electrical energy becomes minimum. This is explained in part by the fact that in (2), as W increases, the denominator may also increase, and this denominator depends on a series of cost factors: b_1, b_2, b_3, C_1, etc. For various types and designs of reactors the effect of each of these factors on the value of the denominator is quite different. For instance, in the case of power reactors of low capacities, where R cannot be very large, the relative value of the second term in the denominator becomes completely insignificant.

Let us examine briefly the possible ways of lowering the value of the denominator in Equation (2).

The first term in the denominator is the difference $b_1 - b_2$ between the initial cost of uranium, enriched with U^{235} to $x_1\%$, and the final cost of the replaced uranium, containing $x_2\%$ U^{235}. This difference characterizes the quantity of U^{235} that has fissioned in the reactor and corresponds to the quantity W. At the present time, judging by data in the literature, enrichment of uranium is effected through the method of gaseous diffusion sepa-

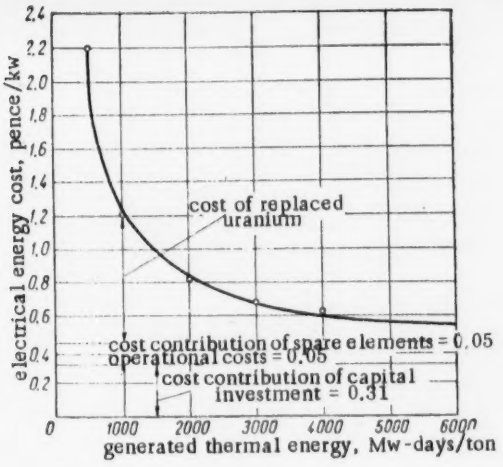
electrical energy cost, pence/kw
cost of replaced uranium
cost contribution of spare elements = 0.05
operational costs = 0.05
cost contribution of capital investment = 0.31
generated thermal energy, Mw-days/ton

Fig. 1. Typical variation of electrical energy cost as a function of thermal energy generated per ton of uranium fuel [1].

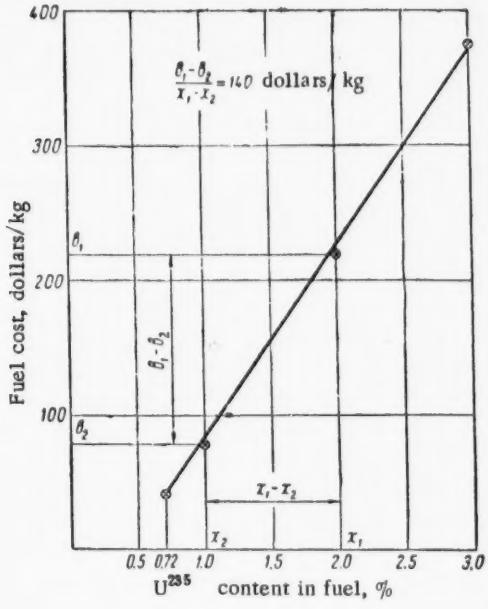

Fig. 2. Variation of cost of uranium with U^{235} content [2].

ration, and therefore its cost is determined by expenditures connected with establishment of this process. For the case of low enrichments (up to 3%), this dependence is practically linear, that is, $(b_1 - b_2) = A(x_1 - x_2)$, where A is the coefficient related to the process of uranium enrichment.

According to published data [2] the variation of uranium cost as a function of its U^{235} content, for the case of low enrichments, may be represented by the graph shown in Figure 2. The expression for this relationship follows:

$$(b_1 - b_2) = 140{,}000(x_1 - x_2). \qquad (3)$$

Here the quantities b_1 and b_2 are given in dollars per ton of uranium, while x_1 and x_2 are given in % (U^{235} content).

Using the equation given above, the first two terms in the denominator of Equation (2) may be transformed in the following manner:

$$(b_1 - b_2) - R\frac{x_1 - x_2}{100} b_3 = \frac{x_1 - x_2}{100}(A - Rb_3), \quad (4)$$

where b_3 is the cost of one ton of plutonium.

The quantity $(A - Rb_3)$ may be made small and possibly negative by the following means: (1) a lowering of the process cost of uranium enrichment; the possibility should not be excluded that as a result of the search for new technical solutions, the dependence of uranium cost on its enrichment will be determined principally by the smallest factor A which at the present time in the USA is equal to 140,000 dollars/ton·% enrichment; (2) the construction of reactors with larger breeding coefficients R; for the reactors of the Calder-Hall power station, this quantity apparently reaches 0.85; in high-power reactors of other types, the coefficient R apparently can be made to equal no less than 0.6 to 0.65; (3) the achievement of a nuclear process within the reactor such that the plutonium formed will be, in the nuclear sense, of the highest quality; according to published data [3], the U.S. Atomic Energy Commission has established plutonium cost schedules for various Pu^{240} contents of from 30 to 45 dollars per gram; since the Pu^{240} content in the total plutonium content bred in the reactor is directly dependent on the quantity W, it follows that the effect of its presence on the general economic indicators of the atomic station must be taken into consideration.

The remaining terms in the denominator of (2) exert a fundamental influence on the economic characteristics of an atomic power station. The values of these terms, as indicated earlier, are determined by: the cost of fabrication of fuel elements, C_1; the fabrication costs (with consideration of the possibility for partial reuse) of various structural elements that are necessary for positioning of the fuel elements in the reactor $(C_2 - C_3)$; by the

reprocessing costs, C_4, of fuel elements unloaded from the reactor, for the purpose of extraction from the used elements of plutonium and uranium. Common to all these costs is the fact that they must be compared to the weight of uranium loaded in the reactor. For this reason the choice of fuel loading, during design of a nuclear reactor, must be considered from this point of view. It may occur that increasing the design loading will basically affect the economic indicators of the atomic station (and this, other conditions being equal, leads to an increase in the operating time T). The development of designs that lead to minimum values of the denominator of Equation (2) and, in particular, the latter three terms of the denominator, is one of the main problems of reactor technology.

For thermal reactors it is not difficult to formulate the following additional relationships:

$$m \simeq 240 \cdot k \cdot a \frac{\eta_{net}}{10^{-6}(100A - Rb_3) + \frac{C_1 + (C_2 - C_3) + C_4}{Q_{th} \cdot T}}, \quad (5)$$

$$m \simeq 240 \cdot k \cdot a \frac{\eta_{net}}{10^{-6}(100A - Rb_3) + \frac{C_1 + (C_2 - C_3) + C_4}{W \cdot g}}. \quad (5')$$

In these expressions 10^{-6} is a factor arrived at through the assumption that heat is generated through the fission of U^{235}; in actuality, for thermal reactors, part of the generated heat comes from the fission of Pu^{239} and Pu^{241}, which decreases somewhat the value of the factor.

The Expressions (5) and (5') are convenient for comparative evaluation of the economy of atomic power stations employing reactors of various types and with various operating procedures. From these expressions it follows in part that if it appears possible to increase the time of an operating run through some enrichment of U^{235} (other conditions being equal) then this measure may prove beneficial from the standpoint of cost of generated electrical energy.

The relationship of m to other quantities, demonstrated by (1), (2), (5) and (5'), does not, of course, reflect all considerations in the complicated question of the economics of electrical energy generated by atomic stations. However, this relationship does allow the evaluation of the effects of the major factors and to some degree explains the existence at the present time, of various technical approaches to the design of various types of power generating nuclear reactors.

For instance it appears that with the identical thermal power, Q_{th}, it is feasible to attempt higher over-all station thermal efficiencies, η_{net}. An increase in the efficiency may be attained through an increase in steam parameters (pressure and temperature) at the turbine inlet. For this reason one of the approaches in power reactor design is the development of reactors that allow attainment of high steam parameters. One such reactor is in the first Soviet atomic power station, others are the reactors of one of the high-power power stations now under construction in the USSR, as well as reactors with a sodium coolant and others.

In achieving the necessary economy in such reactors, the increase of η_{net} (station efficiency) in the numerator of Equations (1), (2), (5) and (5') through the use of high-steam parameters, justifies an increase in the denominator created by the necessary introduction into the core of the reactor of certain additional structural materials (or sodium) which to some extent harms the neutron balance, and produces a relative decrease in R, and therefore in B_{fin} as well. In addition, this leads to some increase in the cost of fuel elements, which may be compensated for by an increase in operating-run duration.

The necessary increase in the value of m may be achieved also through a decrease in the denominator, in particular through a decrease in the value of $(B_{in} - B_{fin})/T$ in Equation (1), which is the cost term for the reactor loading and depends, as previously pointed out, on the U^{235} content in the uranium at the beginning and at the end of the operating run, by the cost of plutonium, the properties of structural materials, fuel elements, etc.

The essence of the technical approaches that are included in the design of reactors that utilize this method for the improvement of economy is included in the following:

1. Without reverting to the as yet costly process of preliminary enrichment of natural uranium, that is, by using uranium with a natural content of U^{235}, it is possible to achieve a relatively low value of B_{in} and a rela-

tively high value of B_{fin}, thus in the final count even under relatively low values of η_{net}, a satisfactory value of $\underline{m}$ may be achieved. This principle in particular is utilized in the reactors of England's Calder Hall, in reactors with heavy-water moderator, and several others. Apparently, for reactors of this type, a relatively low value of the second term in the denominator of (5) and (5') is typical.

2. Utilizing low enrichment uranium, it is possible to use some specific properties of common water for neutron moderator, resulting in the achievement of a relatively high quantity of plutonium in the reactor and also resulting in an increase of the value of B_{fin} and R, that is, finally to lower the value of $(B_{in} - B_{fin})/T$ in Equation (1), or the quantity $(100A - R \cdot b_3)$ in the Expressions (5) and (5'). Calculations show that under certain relationships of enriched uranium cost to the current price of plutonium (even under relatively low steam parameters), an acceptable value of $\underline{m}$ may be achieved in such reactors. The PWR reactor, being assembled near Pittsburgh (USA) is of this type, also the reactors of one of the high-power stations under construction in the USSR and several others.

It is impossible in a short article to examine all the questions connected with the development of economical construction of nuclear reactors. However, it is evident from what has been said, that there are many technical approaches toward the creation of economical power stations, and that there are sometimes distinct differences between the various approaches. Study of these approaches is one of the most interesting and complicated areas of present day technology.

One of the purposes of this article is to describe the design principles for a reactor in which high-steam parameters are to be obtained. Reactors of this type will be installed in one of the atomic power stations currently under construction in the USSR. In the basic design of the reactor are incorporated the results of creative work of a large number of Soviet engineers and physicists, carried out over many years, and also the experience of prolonged operation of the first Soviet atomic power station.

Operation of this station [4-6] showed that: 1) the principles adopted in its design (reactor type, basic parameters, design decisions, etc.) were correct; 2) safeguards for protection of operating personnel and of the surrounding population were dependable; 3) the tubular fuel elements, incorporated for the first time in this reactor, possess good qualities: during operation of the power station not a single fuel element failed, thus proving their operational endurance and suitability for long operating runs, and therefore their ability to achieve high uranium burnups (a high value of W); 4) the nuclear reactor of the uranium-graphite system, fissioning on thermal neutrons and using water coolant, circulated through tubular, replaceable fuel channels, possesses a number of advantageous characteristics, and may be used as the heat source in atomic power stations of high-power output under high-steam parameters.

For this reason it was decided to build an atomic power station of high power output, with uranium-graphite reactors in which (in contradistinction to the reactor of the first Soviet atomic power station) the coolant water will vaporize and will be superheated within the fuel channels.

The thermal power of the reactor was determined from operating conditions of one reactor working in combination with one standard steam turbine and electro-generator of 100 Mw capacity. The scheme of a reactor-turbine block leads to essential operational advantages and increases the reliability of the station when connected into the general electrical supply system of the region.

The standard turbine, VK-100, which was selected for the station, uses steam at 90 atmos a. and a temperature of 500°C. The principal scheme of one block of the power station is shown in Figure 3.

Sources of heat in the reactor are the fuel channels, 1. Part of the fuel channels are cooled by boiling water, and the remainder, by steam, which, in the course of heat exchange, is superheated to required temperature. The circulation of boiling water in the steam-water channels is accomplished by means of the pumps, 2.

The secondary steam, at 110 atmos a., that is obtained in the steam generator, is fed to the superheating channels of the reactor, where it is superheated to a temperature of 510°C, at a pressure of 90 atmos a. and is then fed to the turbine.

Thus, while in the reactor of the first atomic power station superheated steam was obtained in the secondary loop by utilizing subcooled water that circulates through the first loop and emerges from the fuel channels at a pressure of 100 atmos a. and a temperature of 290°C (which allows the steam generator to produce secondary steam of only 12 to 13 atmos a. and 270 to 280°C), the power station described here achieves steam superheats

of 510°C directly within the reactor. The increased steam parameters make possible the operation of the station described here at an efficiency of 35 to 38%, while the efficiency of the first atomic power station was only 15 to 17%.

The decision to generate superheated steam directly in the reactor was made only after a series of calculations and experiments which established the following: 1) the steam superheated within the reactor and fed directly to the turbine had an acceptable level of radioactivity; 2) with salt contents in the superheated steam not greater than 0.05 mg/kg the radioactivity at the surface of the steam loop equipment and turbine was far below the maximum allowable limit, even when considering that all radioactive deposits will occur in the turbine only; 3) the concentration of radioactive aerosols in the areas where the equipment containing radioactive steam and water is located does not exceed allowable limits even under conditions of maximum possible water and steam leakage from the loop (1% of total water weight within the loop per hour) and may be reduced several times by ventilation.

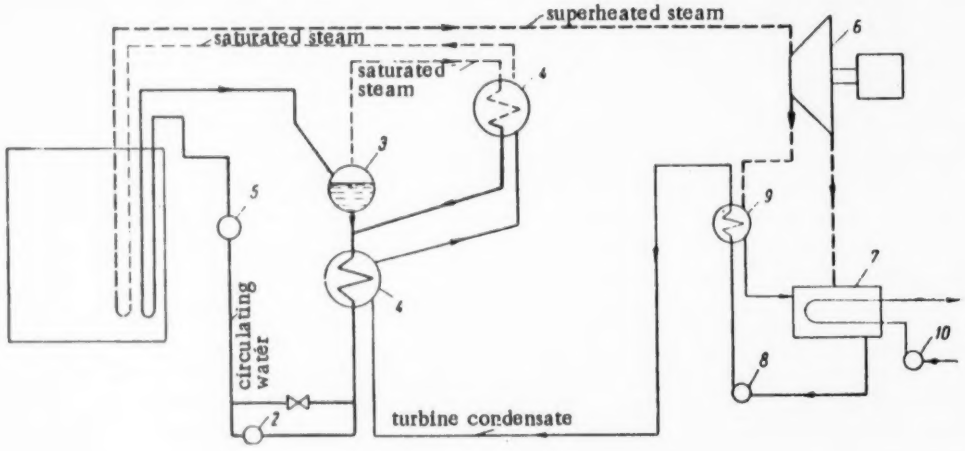

Fig. 3. Principal scheme of a power station with uranium-graphite reactor: 1) reactor; 2) circulating pump; 3) steam separator; 4) steam generator (preheater and vaporizer); 5) collector manifold; 6) turbogenerator; 7) turbine condenser; 8) feed pump; 9) feed water preheater; 10) circulating pump.

Basic characteristics of the reactor:

Thermal power output	285 Mw
Electrical power output	100 Mw
Moderator and reflector	Graphite
Coolant	Water and steam
Steam output	405 tons/hr
Steam temperature at turbine inlet	500°C
Steam pressure at turbine inlet	90 atmos a.
Thermal system efficiency	35 to 38%

The reactor is basically a graphite pile, cylindrical in form, pierced by vertical fuel channels which contain fuel elements of low enrichment uranium. Figure 4 shows a cross section through the main reactor shell and gives some idea of the relative locations of equipment and of the power station and its basic dimensions.

Technical-economic calculations showed that the cost of electricity generated even with initial equipment, will not exceed the cost of electrical energy that is generated by contemporary high-power coal-burning power stations.

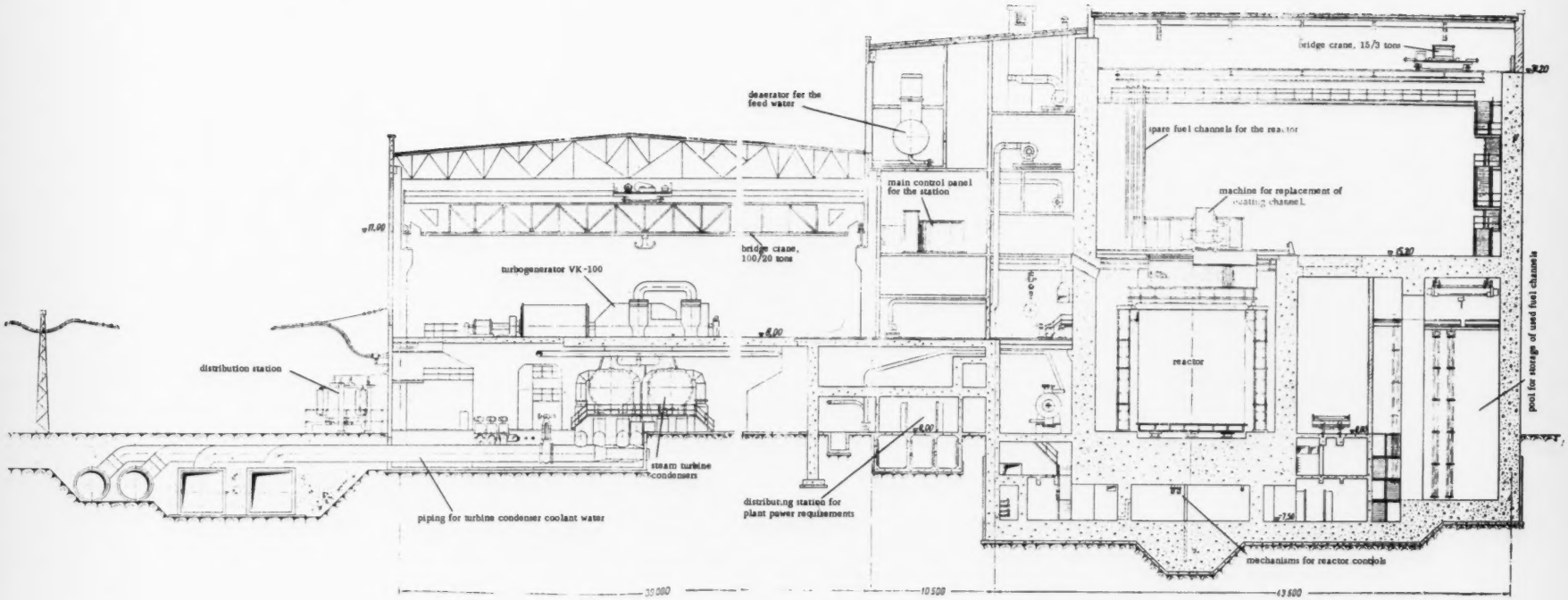
bridge crane, 15/3 tons
deaerator for the feed water
spare fuel channels for the reactor
main control panel for the station
machine for replacement of working channel
bridge crane, 100/20 tons
turbogenerator VK-100
distribution station
reactor
pool for storage of used fuel channels
steam turbine condensers
distributing station for plant power requirements
piping for turbine condenser coolant water
mechanisms for reactor controls
30 000
10 500
43 500

Fig. 4. Cross-section through the building of the power station containing the uranium-graphite reactor.

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GRAPHITE IN REACTOR DESIGN

V.V. Goncharov

REQUIREMENTS FOR A GRAPHITE MODERATOR

Carbon in the form of graphite is one of the most suitable materials for use as a moderator in nuclear reactors.

Graphite has a high melting temperature, possesses good mechanical properties, is easily worked; the production of graphite in large quantities is possible on the basis of existing industrial facilities, at relatively low cost.

A moderator must be very pure. The concentration of many elements must be limited in a moderator, and some elements may be tolerated only in concentrations of several parts per million.

Harmful impurities, having high neutron capture cross sections, include: boron, cadmium, lithium, germanium, the rare earths group (particularly gadolinium), titanium, vanadium, manganese, iron and other elements.

The specific weight of the graphite is very important. The greater the density of the graphite, the greater its slowing down power, since the number of nuclei per unit volume increases as the density. The physical specific weight of graphite is 2.23 g/cm^3. However, the density achieved in fabricated parts is about 1.65 g/cm^3. The specific weight of graphite is directly dependent on a series of factors related to the fabricating technique. It is well known that the graphite in fabricated parts is a porous material; the lower the specific weight of the graphite, the higher its porosity, the greater the amount of air and therefore also nitrogen in the pores. The nitrogen, having a relatively high neutron capture cross section, is a harmful impurity. This explains the effort to obtain graphite parts of maximum density. However, technical capabilities limit the obtainable graphite density, and the larger the fabricated parts, the more difficult it is to obtain high values of specific weight.

BASIC PHYSICAL AND CHEMICAL PROPERTIES OF GRAPHITE AND GRAPHITIC MATERIALS

Graphite is one of the allotropic forms of carbon and has a hexagonal crystal lattice (Figure 1). Within the graphite crystal, atoms of carbon are closely spaced at a distance of 1.46 A at the corners of equilateral hexagons, so that each atom has only three neighboring atoms. The hexagons are distributed in basic parallel planes (layers). The distance between neighboring planes (3.345 A) is greater than the distance between atoms within the hexagon; therefore the binding force between atoms is greater in the horizontal plane than the binding force between planes.

Adjacent parallel planes are displaced relative to each other and their positions are repeated at every other layer. The binding force between atomic layers is maintained by easily displaced electrons. The weak attraction between atomic layers gives the graphite its characteristic unidirectional cohesive strength. The laminar structure causes the variation of graphite properties along different cross sections.

The hardness of graphite on Mohs scale is about 1, which is the result of the ease of fracture along the binding planes. In the perpendicular direction, the hardness of graphite reaches 5.5 and higher.

A consequence of the firm bond between atoms of the hexagonal lattice is the very high fusion temperature of the graphite: 3850° ± 50°C [1, 2].

Because of the presence in the crystal lattice of the mobile electrons, the graphite possesses heat conduct-

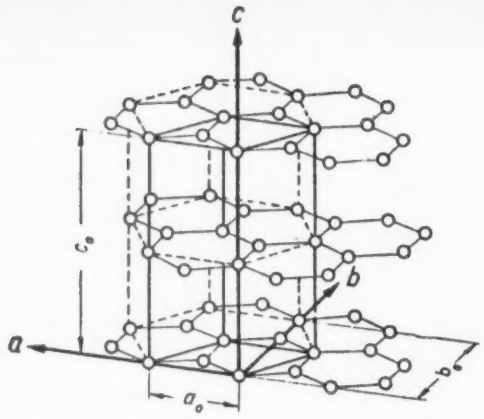

Fig. 1. The crystal lattice of graphite.

ivity and electrical conductivity of the same order as many metals. For this same reason graphite exhibits metallic color and luster.

The crystalline structures of natural and artificial graphites are the same; however, natural graphite crystals are considerably larger and are oriented along one direction, leading to lamination. Artificial graphite, possessing properties similar to those of natural graphite, considerably surpasses it in purity. Natural graphite contains many impurities (usually over 10%).

The average distance between lattices of polycrystalline artificial graphite becomes smaller and nearer to the value for a perfect crystal, as the degree of graphitization of the artificial material increases.

The physical properties of polycrystalline graphite depend to a large extent on the method of preparation. Various methods of preparation yield different dimensions of crystal orientation of the graphite. In connection with this, the graphite is anisotropic; its properties are basically different in the parallel and perpendicular directions relative to the predominant orientation of the basic planes.

The physical properties of artificial graphite may be changed through the choice of raw material and production technology [3, 4].

Tables 1-7 give some physical properties of various types of graphite [3].

TABLE 1

Specific Resistance

Type of part, or graphite	Parallel direction, μohms/cm	Perpendicular direction, μohms/cm
Electrodes	850-1250	–
Blócks	850-1100	–
AGHT	800	1050-1250
AGOT	500-850	–

TABLE 2

Conductivity Coefficient

Temperature, °C	Parallel direction, cal/sec · cm · · °C	Perpendicular direction cal/sec · cm · °C
100	0.35-0.50	0.22-0.35
300	0.28-0.32	0.16-0.28
500	0.20-0.27	0.13-0.20
700	0.16-0.22	0.10-0.16
900	0.13-0.20	0.08-0.13
1100	0.12-0.18	0.07-0.12
1300	0.11-0.17	0.05-0.11

TABLE 3

Temperature, °C	Specific heat (C_p) kcal/mole · °C
25	2.066
127	2.851
327	4.03
527	4.75
727	5.14
927	5.42
1127	5.67

TABLE 4

Specific weight, g/cm³	Conductivity at 20°C, cal/sec · cm · °C•
1.55	0.29
1.60	0.32
1.65	0.35
1.70	0.45
1.75	0.56

•The conductivity is determined in a direction parallel to the direction of extrusion of graphite parts in fabrication.

TABLE 5

Temperature, °C	Coefficient of thermal expansion ($\times 10^{-6}$) for AGOT graphite
0	5.2
250	6.0
500	6.3
750	7.1
1000	8.1

TABLE 6

Type of part	Modulus of elasticity at 20°C ($\times 10^6$ kg/cm^2)
Graphitized electrodes	0.084-0.035
AGOT	0.098-0.148

TABLE 7

Type of part	Strength limits, kg/cm^2*					
	tensile		compressive		bending	
	longitudinal direction	transverse direction	longitudinal direction	transverse direction	longitudinal direction	transverse direction
Graphitized electrodes	35-175	65-90	210-280	210-350	70-350	–
AGOT	–	–	–	–	70-175	70-140
AGHT	170	40	–	–	–	–

*A characteristic of graphite is greater strength at elevated temperatures than at normal temperatures.

The chemical properties of graphite are shown in Table 8.

Oxygen, nitrogen and hydrogen are removed from graphite under vacuum and at high temperatures (1 to $5 \cdot 10^{-3}$ mm Hg); complete degassing occurs at 2150°C. The graphite adsorbs about 0.09% (weight) of water vapors from the atmosphere, when the latter is saturated with water vapor at 20°C.

TABLE 8

Chemical Properties of Graphite

Media	Temperature, °C	Reaction product (or type)
Oxygen	410 and higher	Oxides of carbon
Hydrogen	915 to 1015	Methane (in presence of a catalyst)
Chlorine	up to 2315	No reaction
Nitrogen	3016	No reaction
Water vapor	below 810	Slow reaction
	above 810	Energetic reaction
Carbon dioxide gas	below 810	Slow reaction
	above 810	Oxide of carbon
Concentrated acid (HNO_3 and H_2SO_4)	315 and higher	Anhydride of organic acid (solid product)
Alkalies (in solid form, in an inert atmosphere)	at fusion temperature	Does not react

THE TECHNOLOGY OF PRODUCTION OF GRAPHITIZED PARTS

1. Technology for Fabrication of Common Graphitized Electrodes

Because the production process for graphite parts (blocks) of high purity, for nuclear reactors, consists essentially of operations used in production of common graphitized electrodes, with the same equipment used for both, we will briefly describe this technology [5, 6].

The basic raw ingredients for the production of graphitized electrodes are petroleum coke and binding materials – pitch or resin.

The production of graphitized electrodes consists of the following processes: preliminary pulverization of the raw material, heating of the raw material, crushing, sorting out by size, mixing, pressing, firing, graphitizing, mechanical working. The entire cycle for preparation of graphitized electrodes takes about 2 months to complete.

The carbonaceous raw material (petroleum coke) is pulverized, thus creating the proper condition for the next step in the process – firing.

The firing takes place at a temperature of 1300°C without air. In this step, thermal stability of the carbonaceous raw material is achieved, with transformation of the material into a dense, nonoxidizing state, possessing increased electrical conductivity; the content of volatile fractions in the petroleum coke decreases from 7 to 0.4%.

The fired carbonaceous material is broken up in ball mills. The products of the crushing process in the mill are sorted out by grain size. The aim of the crushing to smaller size, and of the sorting, is the isolation of an aggregate of definite grain size, and the selection of a ratio of coarse to fine grain that will produce parts of minimum porosity and high mechanical strength, after sintering.

Following this, the powders are mixed with a binding agent. The mixing achieves optimum dispersion of the pulverized petroleum coke in a minimum quantity of binding agent, just sufficient for complete immersion of all grains. The next operation – pressing – is thus able to achieve a firm bind between individual grains in the electrode material with minimum porosity.

Pressing of the electrode constituents forms raw electrodes of required dimensions, through one of two means: 1) molding in a closed die, and 2) extrusion through a die, of a mixture that is charged into the press cylinder.

Both methods produce electrodes of uniform quality. As a result of molding, parts of greater density are obtained, but this method cannot be used for the preparation of long electrodes and of small diameter parts. Extrusion is the more rapid and less involved process. Molding is done in steel dies that conform to the shape of the desired part. In graphite that is fabricated by molding in a closed die, the crystal planes orient themselves perpendicularly to the direction of applied pressure. In graphite that has been extruded, the crystal planes orient themselves parallel to the direction of extrusion. The freshly pressed parts are water cooled on concrete surfaces, or in pools, until they have solidified.

The parts are subjected to a firing process to impart high electrical conductivity, rigidity, thermal stability, and mechanical strength to the finished products.

Firing is done in gas fired chambers, or in tunnel ovens, as well as in electrical ovens.

In the firing process volatile constituents are expelled from the binding agent, which is decomposed with the formation of coke, firmly holding the carbon grains in a matrix. The basic component of the electrode, fired petroleum coke, should not produce shrinkage when heated. The parts themselves should not deform during firing. For uniform shrinkage of the entire part (because of coking of the binding agent) heating is done very slowly, which also excludes the possibility of cracking of the electrodes. Further on, the temperature is raised to 800°C (cracking zone). At this stage, complete coking of the binding agent occurs. To ensure complete thermal stability of the electrodes the temperature is raised to 1300°C. After holding this temperature for a time, cooling begins, also taking place slowly to avoid formation of cracks due to nonuniform shrinkage during cooling and the creation of substantial internal pressures.

To improve physical properties of the carbon electrodes, they are graphitized. This process, leading to the formation of artificial graphite, is effected by heating of the fired parts, in an airless environment, to a temperature of over 2200°C. This process consumes about two weeks. As a result the graphitized electrodes assume properties that are distinct from the properties of fired carbon parts, specifically: 1) the electrical resistivity decreases by four times, 2) thermal conductivity increases about thirteen times, 3) ash content decreases from 2.0-2.4 to 0.4-1.0%, 4) physical specific weight from 2.0 to 2.2 g/cm^3, 5) porosity increases by 5 to 8%.

During graphitization a change in structure of the carbon occurs (crystal growth and recrystallization), with a transformation from a colloid-dispersion state to a coarse dispersion state, which is accompanied by expulsion of noncarbonaceous constituents.

During the graphitization process, at a temperature of 1800°C, oxides of silicon, iron and other elements contained in the parts as contaminants, are reduced; some of the reduced elements are volatilized while some form carbides. Under continued temperature increase to 2200°C and higher, some of the carbides dissociate with the formation of vapors of the elements and of graphite.

Thus, the essence of thermal refinement consists in the fact that contaminating additives, in the form of metal carbides, vaporize from the carbonaceous material, as they have low vapor pressures in comparison to the vapor pressures of carbides.

Graphitization takes place in horizontal electrical resistance ovens that operate intermittently; the heat required for graphitization is generated by passage of electrical current through the parts that are to be graphitized and through the powdered carbonaceous material that fills the spaces between consecutive rows of parts, thus forming the electrical resistance of the oven. Graphitized parts together with the fill powder, which is unfired foundry coke, form a so-called "kernel."

A basic requirement of the process is that a uniform temperature must exist over the entire charged volume of the electrical graphitizing oven.

Mechanical working of the graphitized parts imparts the necessary dimensions within established limits. The mechanical working is done with the same type of equipment as is used for working steel.

2. The Technology of Production of Graphitized Parts (Blocks) of High Purity

Production of Graphite for Reactors in the USSR

The first step in the development of a technology for production of graphitized blocks of high purity for nuclear reactors was a study of the finest examples of graphitized electrodes that were produced by our own and foreign electrode industry.

It was established that ash content in these samples amounted to 0.4 to 1.0%, and that boron content was $1.5 \cdot 10^{-4}$ to $4.5 \cdot 10^{-4}$%. Such a high ash and boron content completely eliminated the possibility of adopting such graphite in nuclear reactors, without considering the fact that these limited examples were far from representing all of the contaminants.

Together with this, it was established that ash content in test samples taken from the surfaces of electrodes was considerably greater than ash content in samples taken from the center of the electrode. For instance, one sample contained 0.36% ash at the center while ash content at its surface was equal to 4.5%. Another sample contained 0.394% ash at its center, while in the surface layer to a depth of 2 mm it contained 1.38% ash.

It was essential to determine at what stages of the process and to what extent contamination occurs, both for the raw materials and the semi-finished part.

As was indicated above, to ensure high temperature of graphitization of the electrodes in the electrical resistance furnace, special charging of the oven is essential and a definite sequence of application of electricity is required. The materials of the charge (both the parts and the packing material) contain significant amounts of ash contaminants. In particular, the commonly used packing material, foundry coke, ash content reaches 12%. Because of these contaminants, an atmosphere charged with metal and oxide vapors was created in the graphitization oven at high temperatures, thus leading to contamination of the parts. In cooling the oven, metal and oxide vapors condense and contaminate the surface of the electrodes.

As was indicated earlier, thermal refinement is based on the fact that at high temperatures the contaminants in the graphite vaporize, while the graphite itself, possessing under these conditions low volatility, remains in solid form.

In the presence of graphite the volatility of nonorganic contaminants varies. It has been established that calcium vaporizes most readily, that aluminum vaporizes not as well, and that silicon, iron and boron, vaporize still less. The latter elements remain in the graphite particularly stubbornly, in small quantities.

Near 2200°C all contaminants can, to a significant extent, be expelled and ash content of the graphite will then not exceed 0.1%. However, in order to obtain residual ash content on the order of hundredths of one percent, it is essential to have a temperature considerably higher than 2200°C. But even under these conditions sufficient expulsion of these contaminants, particularly boron and boron carbide is not ensured, since boron carbide has a particularly high dissociation temperature, and therefore it is impossible to completely expel them even in the process of ultra-high temperature thermal refinement.

Experiments confirmed the extreme importance of the purity of the initial raw material for decreasing the ash content of the graphitized final part. However, the use of low ash content petroleum coke could yield the desired effect only when complete cleanliness of all apparatus is maintained.

The ash content in petroleum coke depends on the contaminants in the raw materials (heavy hydrocarbons of petroleum – the initial product for coke production), since during distillation and coking all contaminants are concentrated in the petroleum coke. For this reason, in study and selection of the petroleum coke, particular attention was given to its initial purity and suitability for graphitization.

It was desired to reduce to a minimum not only the quantity of contaminants in the graphite (ash content), but also to change the composition of the contaminants, that is, to decrease the proportions of the more harmful elements. Analyses showed that the composition of contaminants in various batches of graphite varied considerably.

Investigations were carried out to find a cleaner industrial raw material and to develop methods for more intensive refinement. The success of these studies led to the organization in the Soviet Union of production of graphitized blocks of required purity for reactor construction [7].

The initial raw material for preparation of the blocks is one of the variations of petroleum coke, with ash content up to 0.04%. Low ash coke is used also as the packing material in the kernel of the graphitizing oven (packed between the blocks and around them in a layer 200 mm thick). For external insulating layers of 600 to 800 mm thickness, foundry coke is used, thus creating high vapor permeability of the upper part of the oven. The simultaneous processes of thermal and gaseous refinement are effected in graphitizing ovens of ordinary type, but modified for this purpose. Graphitization takes place at temperatures up to 2400°C.

The quality of pure graphite produced by the plants of the Soviet Union for nuclear reactors is exemplified by the following specifications: average ash content – $3 \cdot 10^{-3}$%; boron content – $\sim 2.45 \cdot 10^{-5}$%; specific weight – 1.65 to 1.70 g/cm^3 (in occasional cases batches of graphite of specific weight of 1.8 g/cm^3 are produced).

Production of Graphite for Reactors in the USA

The graphite for the reactors that have been built in the USA was, in general, produced through the technology used for preparation of ordinary graphite electrodes. Raw material for production of the graphite is petroleum coke of various types. Binding material used is coal tar pitch. The petroleum coke is fired and pulverized into particles of various sizes, but definite size distribution, and is then mixed thoroughly with a binding agent until a homogeneous molding compound is obtained. Mixing is done at a temperature that ensures complete liquefaction of the binding agent.

TABLE 9

Contaminant Content of Graphite

Graphite type	Contents, 10^{-4}%						
	ash	B	Al	Ca	Ti	Fe	V
AGX	1500	1.3	20	2000	50	40	70
C-18	1200—2000	1.0	10	1200	35	100	200
AGHT	700—1700	—	—	500	100	<100	<100
AGOT	350—700	—	—	100—200	100	<100	<100
CS	350—700	—	—	—	—	—	<100

Semi-finished parts are prepared by extrusion or press molding; with the aim of expulsion from the parts of volatile fractions, the parts are fired at a temperature of near 900°C.

If an increase in specific weight of the parts is essential, the semi-finished part is saturated with pitch, and is then fired a second time. Following this, the semi-finished parts are subjected to graphitization in an electrical resistance oven (Acheson-oven) at a temperature up to 2800°C. Another method makes possible graphitization in an electrical resistance oven CBF involving a controlled gas environment.

It appears that a graphite of high purity is also obtained through a high temperature gas extraction process that has been proposed by the firm "United Carbon Products Co." In this process purification takes place in a gaseous atmosphere under electrical heating of the blocks to a temperature of about 2500°C. Ash content in the graphite obtained by this method is less than twenty parts per million.

The desired graphite purity that is indicated for reactors is achieved through a careful selection of petroleum coke, through regulation of gaseous environment composition in the graphitizing oven and through control of the corresponding temperature for thermal refinement.

For reactor grade graphite, a coke of low boron content is selected, as well as low vanadium and titanium content, although it is claimed that such selection does not have great significance under the purification methods that are used. During graphitization, petroleum coke is used as fill material, instead of metallurgical coke.

The special graphites AGOT and AGHT that are used in reactors are prepared by this method. AGOT graphite is obtained at the center of the batch, while AGHT graphite is obtained at the outside of the batch, at the oven surfaces [3, 4, 8].

Ash and contaminant content in some reactor graphite types and in common graphite, that is produced in the USA, is indicated in Table 9.

Specific weight of graphite parts, AGHT, is equal to 1.61 to 1.65 g/cm^3 and that of AGOT is 1.65 to 1.72 g/cm^3. Thermal neutron absorption cross section of AGOT graphite is equal to 4.8 mbarns [3].

Production of Reactor Grade Graphite in France

Reactor grade graphite is obtained in France by ordinary methods [9]. Firing and graphitization are conducted in electrical heating ovens. Graphite purity is obtained through observance of necessary precautionary measures at each operation. In newly constructed shops for preparation of graphite, the processes are mechanized, thus allowing reduction of accidental contamination to a minimum. For movement of the graphite raw mass that isobtained after mixing of coke resin, pneumatic conveying is used.

The basic raw materials are petroleum coke and resin. Graphitization is effected at a temperature of up to 2000°C. At the high temperature, the contaminants in the coke are expelled, but not entirely. The purity of the graphite produced at the plant of the Pichenet Co. is exemplified by the following specifications:

Element	B	Ca	H	Fe	Mn	V	Ti	Rare earths
Contents in 10^{-6}	0.3	60	15	15	0.1	23	17	0.1

Thermal neutron absorption cross section of the graphite does not exceed 4.0 mbarns.

Specific weight of graphite parts is 1.69 g/cm^3, porosity is approximately 28%.

The recently published data of Reference [10], concerning the production of reactor grade graphite, are essentially different from the data of [9]. It is indicated that purification of graphite can be carried out through a halide reaction, at a temperature of 2500°C; at these conditions, metallic and nonmetallic contaminants are expelled in the form of chlorides or fluorides. This is the method used for graphite purification at the Pichenet plant.

THE UTILIZATION OF GRAPHITE IN NUCLEAR REACTORS

In the Soviet Union. Graphite is used successfully as the moderator in nuclear reactors.

Graphite was used in the reactor in which the first chain reaction in the USSR was produced. The core and the reflector of this reactor are composed of graphite blocks (prismatic), 100 x 100 x 600 mm in size. The graphite prisms of the core were drilled through with holes at a pitch of 200 mm for installation of uranium slugs. Total graphite weight in the reactor was several hundred tons [11, 12]. Graphite was also used as the moderator in the reactor RFT [13], where the specific weight of graphite blocks in the core was ~ 1.8 g/cm^3. During reactor operation graphite temperature reaches 470°C.

Graphite is also used in the reactor of the first Soviet atomic power station [14, 15].

The graphite pile of the reactor is enclosed in a steel lining, is filled with inert gas (nitrogen or helium). During reactor operation, temperature of the graphite pile at various points reaches 650 to 700°C.

In conformance with the sixth five-year plan several reactors using graphite moderator are being erected in the Soviet Union.

A large atomic station of 400 to 600 Mw electrical power utilizing graphite reactors, similar to the first operating atomic power station, is also being built.

In addition, an experimental atomic power station of 50 electrical Mw, with graphite moderator and sodium coolant is being assembled.

In the USA. In the first nuclear reactor to ever go critical, graphite was used as the moderator. Graphite moderator was used in a series of experimental reactors [16, 17] and also in all the plutonium production reactors at Hanford.

Graphite moderator will be used in the large reactor of the 800 Mw thermal power atomic power station [18]. Recently the experimental sodium reactor SRE, using graphite moderator, went critical; this reactor has a thermal power of 20 Mw and is the prototype for the more powerful sodium graphite reactor SGR, of 250 Mw thermal power [19, 21]. A graphite reactor is planned for the LMFR reactor, which will use liquid metal fuel (solution of uranium in bismuth) for a power station of 210 Mw [22].

In England. The development of atomic power is based on reactors that utilize graphite moderators [23, 24].

Graphite moderator is used by the reactors of the atomic power station at Calder Hall. Graphite for these reactors is manufactured by the British-Acheson Electrode Co. Several experimental reactors using graphite moderators and reflectors have also been built in England (the reactors GLEEP, BEPO and NERO).

Reactors with graphite moderators are used at Windscale, and are intended for plutonium production.

In France. In January, 1956, at Marcoule, in the department of Gar, the G-1 reactor of 40 Mw thermal power, using graphite moderator, was set in operation.

A second graphite reactor, the dual purpose G-2, is also under construction, as well as a series of other graphite moderated reactors [25, 26].

PROPERTY CHANGES IN GRAPHITE UNDER THE ACTION OF REACTOR RADIATION

Under the action of reactor radiation significant changes in graphite properties have been observed.

It was established [11], that there occurs a decrease in thermal conductivity and electrical conductivity of graphite, a change in volume, all of which is connected with the disruption of the crystal lattice of graphite and of changes in its physical constants.

Additional investigations [27] defined more closely the physical nature of the changes in graphite, and solved a series of practical problems connected with design and utilization of graphite nuclear reactors. Samples of graphite were investigated after being placed in a reactor, as well as samples that were cut from the graphite piles of reactors after various periods of reactor operation.

Those changes in the graphite that are of practical significance have been particularly thoroughly investigated: strength, thermal conductivity, and dimensional changes. The presence of very basic changes in graphite

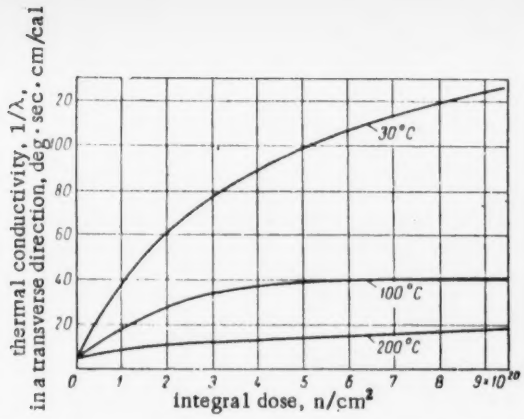

Fig. 2. Changes in thermal conductivity of graphite under neutron irradiation at various temperatures.

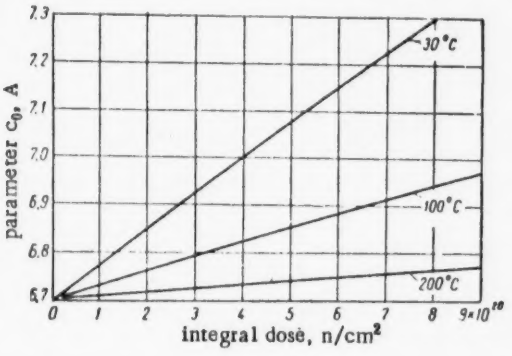

Fig. 3. Changes in lattice parameters of graphite under neutron irradiation at various temperatures.

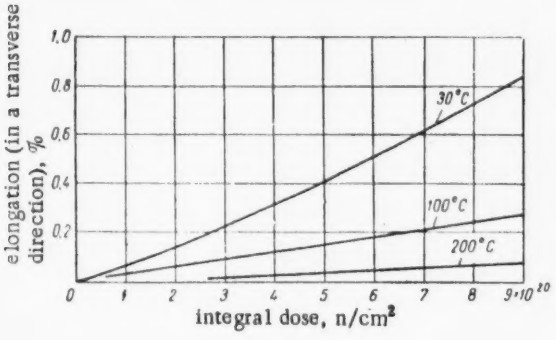

Fig. 4. Changes in linear dimensions of graphite under the action of neutron irradiation at various temperatures.

properties was established, these changes disappearing only after annealing, that is, heating of the graphite to a temperature considerably higher than the temperature at which the graphite was irradiated. For instance, under irradiation of graphite to an integral neutron dose of $\sim 7 \cdot 10^{20}$ n/cm², at a temperature of ~150°C, the electrical conductivity increases by three times, thermal conductivity decreases twenty times, specific volume increases by several percent.

It was further established that during annealing of the graphite, stored energy in the crystal lattice is emitted. Investigations of the quantity of emitted energy and of its mode of emission, as well as its relationship to dose and temperature of irradiation, shows that the quantity of emitted energy grows with increase in integral irradiation dose and decreases with increasing temperature of irradiation.

X-ray diffraction studies conducted by S.T. Konobeevsky, F.P. Butr, V.G. Kuznetsov and N.I. Kotov, showed that under the action of irradiation interplanar distance of the crystal lattice(c_0)increases, while the distance between atoms in one plane (a_0) decreases. These changes in the crystal lattice are the ones that lead to expansion of the graphite. These changes become evident least in graphite that is irradiated at high temperatures.

It was also established that under irradiation there is a dual disruption in structure of the graphite. Primary disruption accumulates quickly to an equilibrium state and leads to changes in the electrical resistivity, the moduli of elasticity and hardness. These disruptions begin to disappear at relatively low temperatures of annealing and are completely removed at temperatures of 500 to 600°C.

Secondary disruptions – volumetric expansion, further changes in thermal conductivity, the appearance of permanent excess electrical resistivity – accumulate with dose considerably more slowly and are evoked only by neutrons of high energy. These disruptions are stable and are removed only at a temperature of 2000°C, that is, at the temperature of recrystallization. The authors of the investigations state that these disruptions of properties are connected with a reduction of crystal size [27].

Results of investigations of the effects of irradiation on the properties of graphite, have also been published in the USA. These investigations have principally established the laws governing the irradiation-induced changes in graphite, analogous to those mentioned above. It is interesting to note the good agreement of the investigations conducted independently in the USSR and the USA.

In the investigations whose results have been published in the USA it is indicated that the radiation induced changes in graphite depend principally on the temperature at which irradiation takes place, and also on the technological process of preparation of the graphite. It was established that under neutron irradiation, mechanical properties of artificial graphite – hardness and strength – increase, thermal and electrical conductivities decrease, and there are dimensional changes in the samples. Together with this, potential energy is stored in the crystal lattice.

Under irradiation, graphite samples at a temperature near 30°C and integral dose of about $2 \cdot 10^{21}$ n/cm^2, mechanical strength doubles, thermal conductivity decreases 50 times, linear expansion of samples by ~3% is observed, as is a storage of energy of ~500 cal/g. Mechanisms of these effects are not yet fully explained [4].

The results mentioned above were obtained by experimental irradiation of graphite in the Hanford reactors.

Figures 2, 3 and 4 show changes in thermal resistivity (the inverse of thermal conductivity), of the parameter c_0 of the crystalline lattice and of linear dimension changes resulting from irradiation of graphite samples at temperatures of 30, 100, and 200°C [21]. It is seen from the figures that the degree of radiation damage in the graphite is decreased significantly with increasing temperature at which irradiation takes place.

Under irradiation in the MTR reactor, at a temperature of 30 to 50°C, graphite samples that received an integral dose of $20 \cdot 10^{20}$ n/cm^2 showed maximum increase in the parameter c_0 from 6.7 A to about 8.0 A, which corresponds to macroscopic dimensional changes of the sample (expansion) up to 5% [4]. It was established that radiation damage could be removed by annealing. The degree of restoration of physical properties of irradiated graphite depends on the temperature of annealing, but for complete restoration of initial properties, annealing must be conducted at a temperature above 2000°C, that is, near to graphitization temperature.

Some radiation damage in graphite that is irradiated at low temperatures may be removed by increasing the temperature at which irradiation takes place (so-called "nuclear" annealing) and this temperature can be considerably lower than the temperature that is necessary for removal of radiation damage by annealing without irradiation.

Radiation damage in graphite may be decreased not only by increasing the temperature of irradiation, but by changes in the method of production of the graphite as well. In connection with the fact that changes in graphite properties under irradiation create some complications in reactor operation, it is quite important to produce graphite that possesses high physical stability under irradiation.

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EFFICIENCY OF AN ATOMIC POWER GENERATING INSTALLATION*

I. I. Novikov

In an atomic power installation such as an atomic electric power station or an atomic propulsion power plant, the energy of fission of the nuclei, emitted in the form of heat, is transformed first into mechanical and then into electrical energy (if that is the purpose of the installation). This transformation of energy is effected through a thermodynamic cycle, whose parameters determine all estimates of the process efficiency for the entire atomic power generating installation.

From the aggregate of various parameters defining the thermodynamic cycle the so-called optimum parameters, which under the conditions of a given atomic power installation lead to most efficient operation, may be identified, thus yielding the optimum value of the over-all efficiency of the installation.

The process of transformation of energy in an atomic power installation is well known. In the atomic reactor a quantity of heat, Q, is emitted as a result of fission of the nuclei of the atomic fuel, the heat being emitted at some average temperature T_a. This quantity of heat is transferred to a coolant which removes the heat from the reactor and transfers it to the working fluid of the thermodynamic cycle; in principle the working fluid could be the primary reactor coolant, but for a number of reasons this has not yet been realized or is not yet effective in present atomic power installations. As a result of the transfer and transport of heat the temperature of the working fluid increases from T_2 to T_1; let us designate the average temperature of the working fluid in the area of heating of the working fluid as T_r. T_r is lower than the average temperature of the coolant T_t, while the latter is lower than the temperature T_a of the reactor.

On the basis of the heat, Q, at initial temperature T_a, ideally the maximum amount of useful work is equal to

$$L = Q\left(1 - \frac{T_0}{T_a}\right),$$

could be produced, where T_0 is the temperature of the surrounding medium (i.e., the atmosphere). In reality, due to the irreversibility of the heat transfer processes in an atomic power installation, or more accurately in its power producing section, a quantity of useful work, L, is produced, not exceeding the value $Q\left(1 - \frac{T_0}{T_p}\right)$ which represents the theoretically useful output of the entire installation. Because of the irreversibility of the thermodynamic cycle, the actual useful output will be still lower and equal to the expression $Q\left[1 - \frac{T_0}{T_p}(1 + A)\right]$. In this expression, A is a positive quantity, dependent on the degree of irreversibility of the thermodynamic cycle and numerically equal to the ratio of increase of entropy of this system (i.e., the sum of the entropy increase in the heating and cooling fluids in the processes of compression and expansion of the working medium) for one cycle, to the change in entropy of the working medium in the heating process; in the general case A depends on the temperature T_r, but usually to such a low degree that in approximation this quantity may be considered to be independent of T_r.

In a cycle with low value of work of compression compared to expansion energy of the working fluid,

* Literature survey.

$$A = (1 - \eta_T) \frac{T_p - T_0}{T_0},$$

where η_T is the internal relative efficiency of the thermal prime mover (typically a turbine).

From the preceding it follows that in an atomic power installation the useful efficiency is equal to the ratio L_{act}/L, that is, to $[T_p - T_0(1+A)]/T_a - T_0$, while the actual useful output of the installation, and consequently the total power capacity of the installation (neglecting mechanical efficiency), is equal to

$$L_{act} = Q\left[1 - \frac{T_0}{T_p}(1+A)\right]. \quad (1)$$

Some part of the energy L_{act} is used for services within the installation, in particular for pumping the primary coolant. This portion of the energy depends on the nature of the primary coolant and on the design of the installation.

Considering heat losses in the installation amounting to αQ, the expression for L_{act} becomes

$$L_{act} = (1-\alpha) Q\left[1 - \frac{T_0}{T_p}(1+A)\right]. \quad (2)$$

It should be noted that heat losses in the reactor, as well as in reactor accessory equipment, as a rule are insignificant [1].

The quantity of heat abstracted from the reactor, Q, increases with increase of the temperature difference $T_a - T$. However, the temperature in a primary coolant is always greater than the temperature of the working fluid which it heats and on the average is equal to $T_T = T_r + \epsilon$ where ϵ is a positive quantity representing the average value of temperature difference between primary coolant and working fluid, in the process of heat delivery to the working fluid. Therefore, $T_a - T_T = T_a - T_r - \epsilon$ on the average and, consequently, Q is proportional to $(T_a - T_r - \epsilon)$, that is Q decreases as T_r increases. Since L_{act} is equal to the product of two quantities, one of which decreases as T_r increases while the other quantity increases; with given values of T_a, T_0 and ϵ, held constant, the value of L_{act} passes through a maximum as T_r increases.

The average temperature in the reactor, T_a, is determined primarily by the maximum allowable temperature of the fuel element cladding and at the present time, depending upon the cladding material, is equal to 250 to 650°C; the average temperature difference between the coolant and the working fluid, ϵ, depends principally on the choice of working fluid used in the thermodynamic cycle.

The optimum method of operation of an atomic electric power station depends upon certain definite conditions and characteristics of the installation. However, in many cases it may be considered that optimum conditions are those under which maximum power output of the installation is achieved. For atomic electric power stations this requirement was formulated by A. I. Alikhanov and his co-workers [2]. Other authors [3] state this requirement also, but somewhat less emphatically. In contrast to combustion electric power stations, the portion of generated energy cost due to fuel expenditure in an atomic electric power station is far smaller than other costs, and in particular is far below capital investment costs per unit installed power. Therefore such a station will be most economical when its operating level is at maximum power, when capital investment costs per unit of installed power are minimized and the cost of generated electrical energy is lowest. For other atomic installations the necessity for maximum power level operation is even more obvious.

It was pointed out earlier that the useful energy generated by an atomic electric power station, and

consequently the power level of the station are functions of the average temperature T_r of the working fluid at the point of heat transfer to this fluid, when the values of the T_a and ϵ are fixed. This function reaches a maximum value at some optimum value of the temperature T_r, which will from now on be designated as T'. Knowing the operating conditions of an atomic electric power station, an accurate value of the optimum temperature T' may be calculated. However, there is an approximate formula that makes it quite simple to determine an approximate value of the optimum temperature of the working coolant. This formula is very useful for estimating calculations, and was first given by Yvon and others [4]. Since it was proposed by the authors without derivation, it is useful to give here a somewhat approximate but very simple derivation of this formula.

Let us suppose that all coefficients in the expression for L_{act} that are obtained after substitution in Equation (2) of the expression $Q = K(T_a - T_p - \epsilon)$, are constants; such an assumption is justified when T_a and ϵ are fixed, since the heat-transfer coefficient K varies very slowly with temperature. Then

$$L_{act} = B(T_a - T_p - \varepsilon)\left[1 - \frac{T_0}{T_p}(1+A)\right],$$

where A and B are considered to be constant quantities, while T_0, T_a and ϵ have fixed values. From the condition that the function L_{act} must be a maximum we find the optimum temperature T':

$$T' = \sqrt{(T_a - \varepsilon)\, T_0 (1+A)}\,. \tag{3}$$

If we neglect the irreversibility of the processes in the thermodynamic cycle, that is, if A equals 0 then

$$T' = \sqrt{(T_a - \varepsilon)\, T_0}\,. \tag{4}$$

The value of ϵ, which is small compared with T_a, in a number of cases may also be neglected, which leads to:

$$T' = \sqrt{T_a \cdot T_0}\,. \tag{5}$$

This is the approximate formula for T' which may be used for initial estimates of the optimum average temperature of heat transfer to the working fluid in the thermodynamic cycle of an atomic installation. It should be understood that this formula yields only an approximate value of the temperature T'.

By using the formula for T' it is easy to determine the value of the efficiency of the atomic power installation. The efficiency η_e is the ratio of the generated useful energy L_{act} to the quantity of heat evolved in the reactor, Q, that is:

$$\eta_e = (1-\alpha)\left(1 - \sqrt{\frac{T_0(1+A)}{T_a - \varepsilon}}\right). \tag{6}$$

If we neglect heat losses and the irreversibility of the thermodynamic cycle and if we neglect ϵ, then we get the following expression for η_e (which in this case is also equal to thermal efficiency):

$$\eta_e = 1 - \sqrt{\frac{T_0}{T_a}}\,. \tag{7}$$

It should be understood that the value of installation efficiency, when temperature is optimum, T', is not maximum and, in contrast to the useful output or useful power of the installation, η_e does not pass through a maximum value as the average working fluid temperature is increased but merely increases uniformly. Because of this the maximum value of η_e is found when the temperature of the working fluid in the thermodynamic cycle is maximum, that is, when this temperature approaches the temperature of the reactor. However, in this case the useful energy output of the installation would be equal to 0.

The approximate Equations (3) - (7) do not depend on the nature of the primary coolant, that is, they may be used for all types of atomic power installations.

It follows from these formulas that as temperature in the reactor increases (i.e., as the maximum allowable temperature of the fuel element increases) the average temperature, the working fluid temperature (T'), and the installation efficiency all increase. The average working temperature of the working fluid increases slowly while the efficiency increases quite rapidly. Thus as T_a increases by a factor of 2 the temperature T' increases by about 40%, while η_e increases by a factor of almost 2. The efficiency of both atomic electric power stations and combustion electric power stations may be improved through heat regeneration. However, the role of heat regeneration under conditions in an atomic installation is comparatively less important than it is in a steam installation. This is explained by the fact that regenerative heating of the working fluid to a high temperature leads to a loss in gross power output of the installation; therefore it is more feasible to use regenerative heating up to temperatures that are low in comparison to temperatures that are feasible for steam power installations. A number of investigators [1], [3] recommend, for instance, that regenerative heating of the water be effected to 120-150° and to even lower temperatures; in steam power installations under analogous conditions feed water is preheated to 205-215°.

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RESEARCH IN HIGH-ENERGY PARTICLE PHYSICS PERFORMED ON THE SYNCHROCYCLOTRON OF THE LABORATORY FOR NUCLEAR PROBLEMS OF THE JOINT INSTITUTE FOR NUCLEAR RESEARCH

V.P. Dzhelepov and B.M. Pontecorvo

INTRODUCTION

During the forty years of the existence of the Soviet State enormous successes have been achieved in various fields of native science and technology. Particularly rapid during these years was the development of the science of the atomic nucleus. The last fifteen years of its development, both in the Soviet Union and in the economically most highly developed foreign countries (USA and England), have led to the successful solution of many most important problems in the practical use of atomic energy; among these are the design of powerful atomic reactors and electric power stations, and the appearance of a new field of technology, that of nuclear engineering. The basic scientific research on which this technology rests is that involving low-energy particles.

This same period of development in the history of nuclear science is characterized by the birth of a new field in nuclear physics, that of high-energy and very high-energy particles and powerful accelerators. The history of this field is almost entirely contained within the last decade, and it has not yet been used to solve any practical problems.

Basic research in this new field of physics has been centered about the nature and properties of elementary particles such as nucleons, mesons, hyperons, and anti-particles, which are the simplest of the presently known structural elements of matter.

Research of various kinds performed with cosmic rays and high-energy accelerators has shown that elementary particles can be produced by the collision of particles with energies of the order of millions and billions of electron volts. The primary goals of high-energy and very high-energy physics are the most complete determination possible of the set of all elementary particles, the discovery of their mutual interactions, and the study of the processes by which particles are transformed into each other.

It is significant that physicists at present know of twenty-six different elementary particles and that, in spite of the titanic efforts of the world's scientists, the fundamental interaction law between nucleons, the principal structural elements of the nucleus, has not yet been established. One may thus imagine how wide are the unknown horizons of this new field of physics. In addition, the experience of many centuries in the development of global science shows that on entering a large new field of knowledge scientists usually learn from it more than they had anticipated which is both important in principle and useful for humanity.

All of this defines the great expectations of high-energy particle research.

In our present article we shall attempt to give some idea of the basic scientific research performed by Soviet physicists with high-energy particles on the world's largest synchrocyclotron in the Laboratory for Nuclear Problems of the Joint Institute for Nuclear Research.*

*Wishing to present as fully as possible the results of the basic research performed on the six-meter synchrocyclotron from its inceptions and intending the article for a wider circle of readers than is usual, we have chosen to present the material in the form of a compressed text and figures provided with detailed captions taken from original works. We do not treat the large amount of research which was performed by radiochemical methods. Many of

Initiation of the Synchrocyclotron and Characteristics of the High-Energy Particle Beam

The beginning of systematic and detailed research in this field of physics in our country was on December 14, 1949 when the five-meter synchrocyclotron was put into operation at the Institute for Nuclear Problems of the Academy of Sciences, USSR, now the Laboratory for Nuclear Problems of the Joint Institute for Nuclear Research. The instrument yielded 280 Mev deuterons and 560 Mev α-particles [1]. Almost at the same time a synchrotron accelerating electrons to 250 Mev was put into operation at the Physical Institute of the Academy of Sciences, USSR.* The construction of high-energy synchrocyclotrons, which are large and complex engineering projects, was possible only in the most highly developed capitalistic countries (USA, England). Therefore, the synchrocyclotron of the Joint Institute for Nuclear Research is a clear indication of the high level of development of industry and culture attained in the USSR. The large effort devoted to the construction of high-energy accelerators in our country is a concrete result of the exceptional attention and care devoted by the Communist Party, the Soviet Government, and the people to the development of advanced science.

The operation of high-energy accelerators is based on the principle of phase stability of particle motion in resonant cyclic accelerators, discovered by V.I. Veksler (1944) and by E. McMillan (1945).

The construction of the high-energy synchrocyclotron was the result of nearly three years of intense activity of a large group of scientists and engineers from many scientific research institutes. For many years these operations were within the field of interest and activity of Academician I.V. Kurchatov, which was a fruitful influence on their successful solution.

The basic equipment for this high-energy accelerator was prepared in the factories of the ministry of electric industry of the USSR.

At the end of 1950, the five-meter synchrocyclotron was transformed to accelerate protons to an energy of about 500 Mev [1]. Much of the first physical research on the accelerator was devoted to determining the parameters of the high-energy particle beams obtained (intensity, energy and angular distributions, etc.). Table 1 gives the fundamental results of these experiments for various modes of operation of the accelerator.

The nuclear research performed on the five-meter synchrocyclotron will be described later.

Reconstruction of the Accelerator and its Present State

In 1953, after a large program of nuclear research involving deuterons, α-particles, and 500 Mev protons had been completed, the accelerator was reconstructed. The diameter of the pole pieces of the electromagnet was increased to six meters and the energy of the accelerated protons was raised to 680 Mev [1]. The building in which the accelerator is located and a general view of the six-meter synchrocyclotron are shown in Figs. 1 and 2.**

During the reconstruction, a measuring pavillion well shielded from stray radiation by massive concrete, a meson laboratory, and a small room for polarized proton experiments were constructed (Figure 3). The shielding wall of the pavillion contains a large opening for collimators and for extracting the beams.

Improvement of the accelerating conditions in the central region of the chamber, which was accomplished this year, made it possible to increase the proton current at the output by a factor of almost 2, raising it from 0.3 μa [1] to 0.5 μa [4].

There are fourteen different types of beams extracted from the accelerator into the atmosphere [5, 6], namely protons, neutrons, $\pi^{\pm}$- and $\mu^{\pm}$-mesons, γ-rays, etc. (Figure 3). The protons are extracted by exciting radial vibrations, a method which has been developed in detail in our Laboratory [7]. The density of the proton beam as it enters the measuring pavillion is increased further by focusing with the aid of quadrupole lenses [8], so that

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the results obtained by these methods have been presented at sessions of the Soviet Academy of Sciences on the Peaceful Uses of Atomic Energy (see Session AN SSSR on Peaceful Uses of Atomic Energy (Div. Chem. Sci.) (Izd. AN SSSR, 1955)). Because our aim was to describe the work performed by Soviet physicists on the accelerator, works performed on foreign high-energy accelerators are not discussed and are not cited.

*In our article we shall deal only with that research which has been performed on the synchrocyclotron.

**The design details of the six-meter synchrocyclotron have been described earlier in several special articles [1-3] and we shall therefore not go into them in the present work.

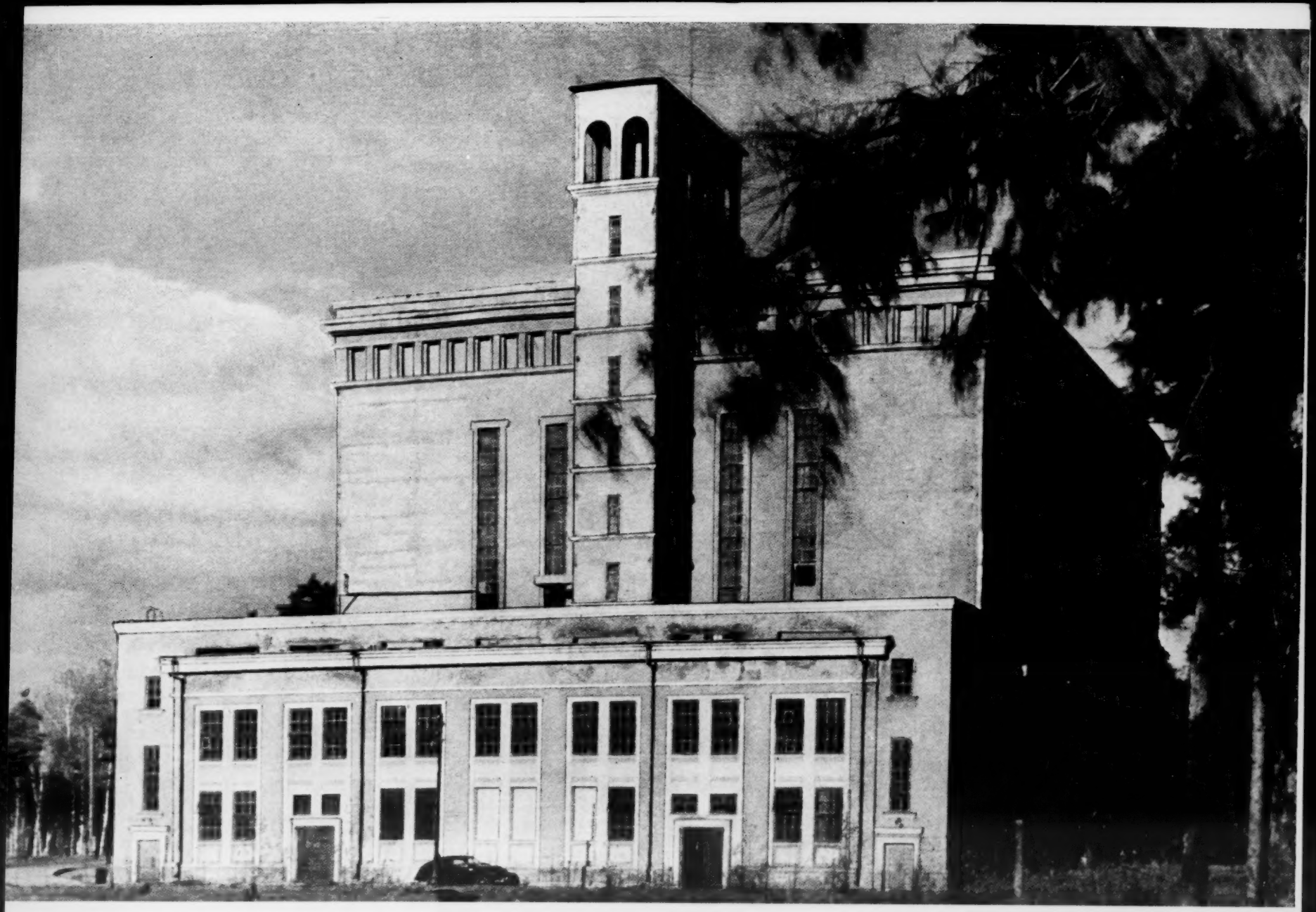

Fig. 1. The building in which the synchrocyclotron is located.

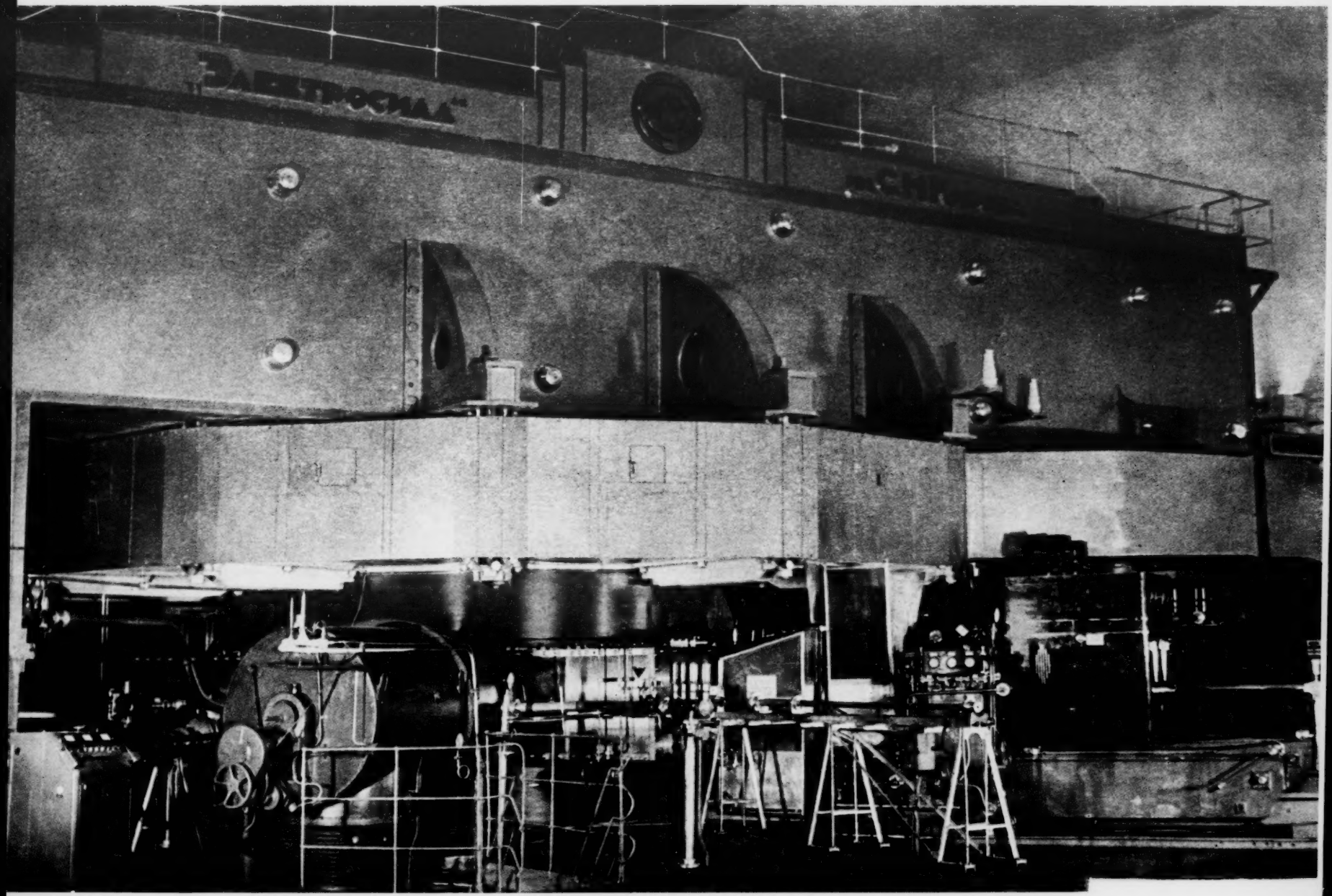

Fig. 2. Over-all view of the synchrocyclotron.

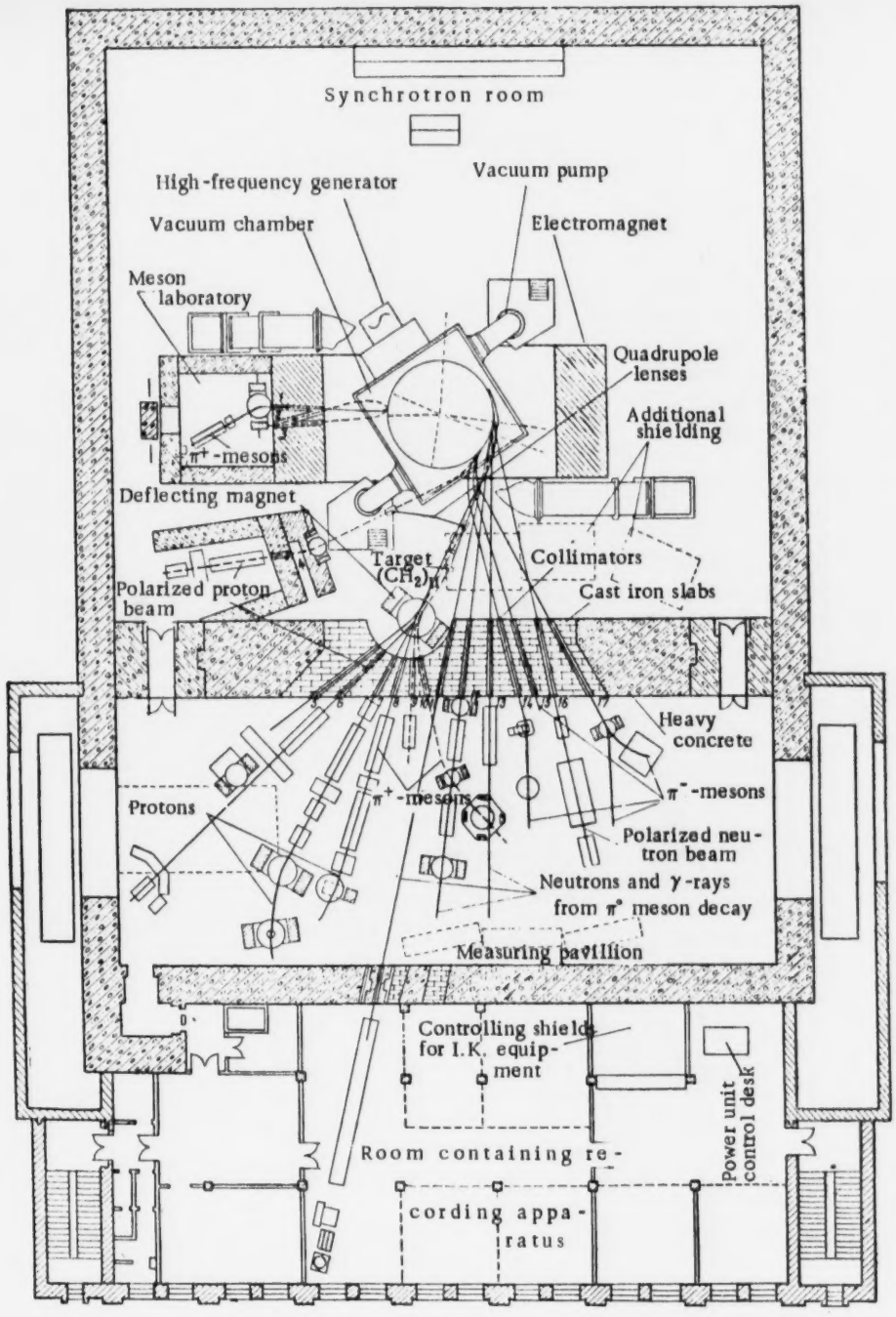

Fig. 3. Plan of the building and diagram of particle beams from the six-meter synchrocyclotron.

at a distance of 15 m from the exit window of the accelerator chamber this density is $1.5 \cdot 10^9$ protons/cm^2 · sec.

The high density of the extracted proton beam has made it possible to form several other high-energy particle beams on external targets: three π-meson beams (collimators 8, 9, 10) and one polarized proton beam (collimator 6) (Figure 3). In order to increase the charged-particle beam densities, in addition to the quadrupole

TABLE 1

Basic Parameters of the Five-Meter Synchrocyclotron Beam

	Accelerated particles and their energies		
	deuterons, 280 Mev	α-particles, 560 Mev	protons, 480 Mev
Current on an internal target, μa	1	0.025	0.2-0.3
Density of extracted beam at 10 m from the magnetic channel, $cm^{-2} \cdot sec^{-1}$	–	–	$1 \cdot 10^6$ (E_p = 460 Mev)
Neutron beam density at the maximum of its angular distribution 2 m from an internal target, $cm^{-2} \cdot sec^{-1}$	$8 \cdot 10^7$	$2 \cdot 10^5$	$5 \cdot 10^6$
Neutron energy at the maximum of the energy distribution, Mev	120	120	380
Half-width of the neutron angular distribution, rad	0.17	0.35	0.55
Process giving rise to neutrons	Stripping	α-particle splitting	Exchange interaction

TABLE 2

High-Energy Particle Beam Intensities from the Six-Meter Synchrocyclotron in the Measuring Pavillion, the Meson Laboratory and the Polarized-Particle Laboratory

Particles	Energy, Mev	Collimator number	Beam density, $cm^{-2} \cdot sec^{-1}$
Protons	675 ± 6	7; as well as 6 or 8	$1.5 \cdot 10^9$
Polarized protons	640 ± 10	*4*	$4 \cdot 10^5$
	610	*6*	$6 \cdot 10^5$
Neutrons	Over the whole energy spectrum $500 \leqslant E_n \leqslant 650$	*11, 12, 13*	$(3 \div 4) \cdot 10^4$
Polarized neutrons	Over the whole energy spectrum $450 \leqslant E_n \leqslant 600$	*16*	10^4
π^+-mesons	150	*8*	450
	300	*8*	1000
	310	*9*	1600
	360	*8*	150
π^--mesons	300	*1*	500
	330	*1*	200
	370	*3*	70
μ^+-mesons	90	*8*	$20 \div 30$
μ^--mesons	25	*17*	60
γ-rays from π^0-meson decay	$10 \leqslant E_\gamma \leqslant 600$	*12*	$3 \cdot 10^3$

lenses we are at present using also special focusing apparatus developed in our Laboratory [9] located in the gaps of the deflecting electromagnets.

Table 2 gives data on the densities and energies of the particles in the various extracted beams as of July, 1957.

At the beginning of 1957 the operating time of the accelerator was raised from 100 hr [1] to 140 hr per week.

The increase in the particle beam intensities and the operating time of the synchrocyclotron have greatly increased the experimental possibilities and have made it possible to go on to the study of such low-probability effects as meson production by mesons near threshold.

Before going on to a description of the results of investigations performed on the synchrocyclotron since it was first put into operation, we note that part of them have already been described in review papers at the 1955 Session of the Academy of Sciences, USSR on the Peaceful Uses of Atomic Energy [10].

Some Experimental Research with 280 Mev Deuterons and 560 Mev α-Particles

The deuterons and α-particles obtained on the five-meter synchrocyclotron had energies greater by a factor of one-and-one-half than on American accelerators, which made it possible to extend the study of nuclear processes involving these particles to higher energies, as well as to perform some new types of experiments.

In this section we shall note very briefly the basic work performed when the machine was used to accelerate deuterons and α-particles (the first half of 1950).

Determination of the Masses of Mesons Produced by the Action of 500 Mev Particles

In 1949-1950 the question of the existence of mesons with different masses in cosmic rays was very often raised. With this in mind, the five-meter synchrocyclotron was used to perform mass-analyses on mesons produced by 500 Mev particles.

The experiments were performed separately by two experimental groups using different methods, and showed that 560 Mev α-particles [11, 12] and 480 Mev protons [13] yield only π-mesons. The yield of mesons of other masses, if they are produced at all, was found [13] to be smaller than the negative π-meson yield by a factor of at least 200.

Nuclear Fission Induced by π-Mesons

Another, also new, experiment was the attempt to observe the fission of heavy nuclei by negative π-mesons stopped in photographic emulsions containing uranium and tungsten. After the first discovery [14, 15] of this process it was studied more fully [16].

Disintegration of 560 Mev α-Particles into Individual Nucleons

It was found [17] that when a beam of 560 Mev α-particles is incident on internal targets of various different substances, there arise intense beams of neutrons and protons with a mean energy of about 120 Mev, directed into a relatively narrow cone along the direction of motion of the α-particles. Some of the results of these experiments with respect to the neutron flux, angular distribution, and energy are given in Table 1 (Column 2). In experiments on α-particle irradiation of photographic emulsions which were performed at the same time, it was established that there is a relatively high probability for nuclear events accompanied by the emission of one or two protons in a direction close to the incident α-particle direction, and with energy equal, on the average, to 1/4 of the α-particle energy [18].

All these facts lead to the conclusion that as a result of collisions there is a high probability that an α-particle incident on a nucleus may be completely broken up, with its nucleons being emitted into a relatively narrow beam about the incident α-particle direction. It is established on the basis of the total neutron yield [17] that the splitting of 560 Mev α-particles is hardly less probable than stripping of 280 Mev deuterons (see Table 1).

Deuteron Stripping

This phenomenon was discovered in Berkeley and was studied there on 190 Mev deuterons. This process was studied at our laboratory [19] for 280 Mev deuterons incident on various targets. Some of the data obtained in this work is shown in Table 1 (Column 1). It is found that the angular distribution of the neutrons obtained in this process, as well as the total cross section for the reaction, is in satisfactory agreement with theoretical results based on concepts developed by R. Serber.

The Discovery of Hard γ-Radiation from a Target in the Synchrocyclotron

In experiments [20] involving bombarding an internal target by 560 Mev α-particles, high-energy γ-radiation which seemed to be due to decay of π^0-mesons produced in the process, was observed.

Nuclear Fission Induced by Neutrons

A new phenomenon, first discovered in experiments with 120 Mev neutrons, was the fission of elements in the middle regions of the periodic table such as dysprosium, erbium, and rhodium [21]. It should be noted that at about the same time radiochemical methods had established the fission of silver when bombarded by 560 Mev

α-particles [22]. Since, according to theory [23], fission in this part of the periodic table should occur primarily if the nucleus is in excited states, the results of these experiments were the first verification of the existence of such a mechanism for nuclear fission. The fission of heavier elements (with $Z \geq 73$) induced by high-energy neutrons was also studied [21, 24].

Artificial α-Radioactivity

The formation of α-active nuclei by the bombardment of various targets by 560 Mev α-particles was investigated [25]. This led to the discovery of the previously unknown α-active nuclei gadolinium, terbium, and dysprosium, which result from holmium, ytterbium, terbium, and erbium.

Several works were devoted to nuclear events induced by π-mesons [26] and high-energy deuterons [27]. The interaction of high-energy neutrons with nuclei was also studied [28]. The emission of secondary neutrons was investigated [29] for nuclei (from berryllium to lead) bombarded by neutrons with mean energies of 120 and 380 Mev.

Elastic Scattering of Nucleons by Nucleons

Occupying an important position among the problems of modern nuclear physics is that of the forces acting between nucleons.

Experiments on the scattering of nucleons, performed with low-energy particles, made it possible to establish that nuclear forces are of a nature other than electromagnetic, differing from the latter in their high intensity, small radius of action, and their complicated dependence on the particle spins.

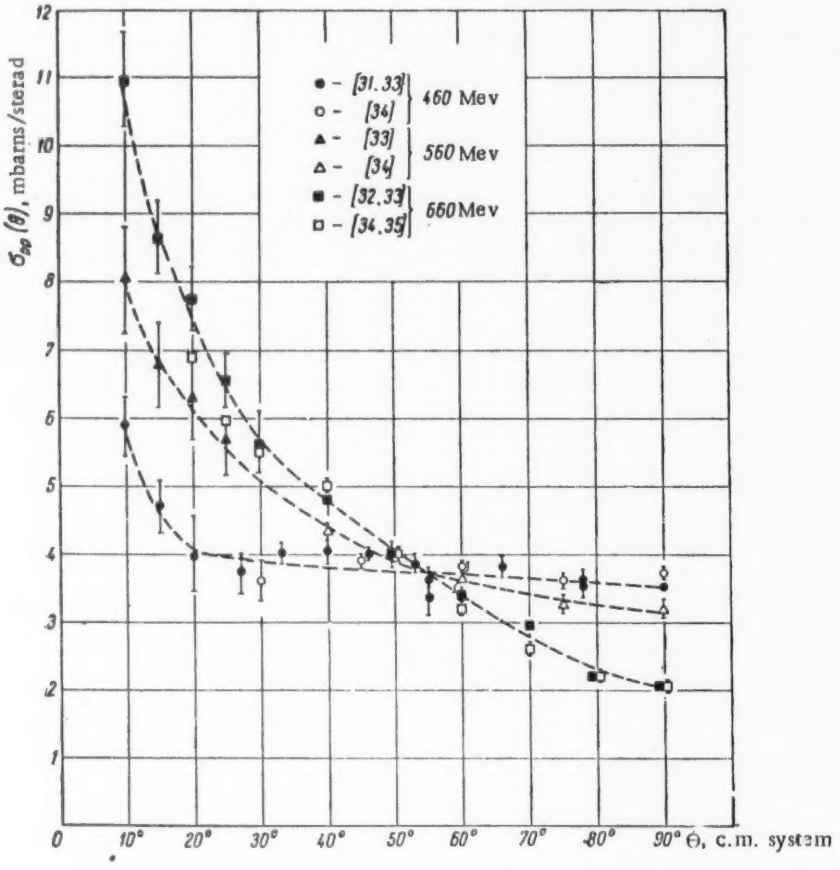

Fig. 4. Elastic proton-proton scattering for 460, 560 and 660 Mev.

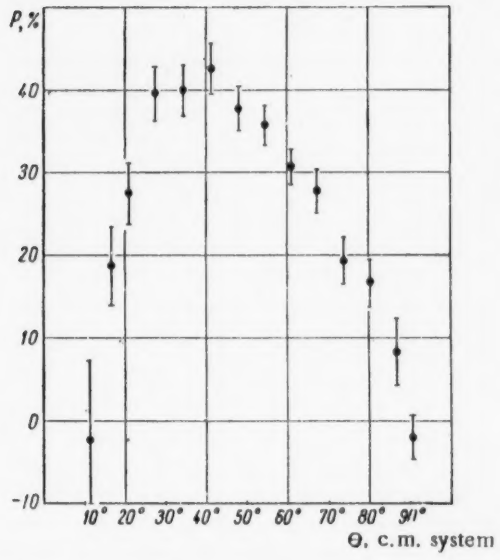

Fig. 5. The angular dependence of the polarization $P(\theta)$ in 635 Mev elastic proton-proton scattering. Analysis of the data allows one to conclude that the triplet F state contributed noticeably to the scattering.

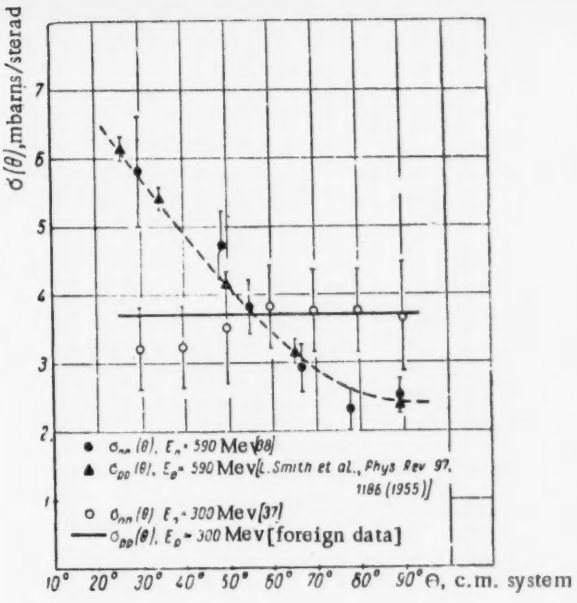

Fig. 6. Elastic neutron-neutron scattering for 300 and 590 Mev.

Many other experimental facts indicate yet another important property of these forces, namely their charge symmetry (the approximate equality of the nuclear interaction between two protons or between two neutrons), which makes it possible to formulate the far-reaching hypothesis of the charge-independence of the nucleon interaction. At the basis of this hypothesis lies the assumption of the equality of the interaction between two arbitrary pairs of nucleons in states with equal total spins and orbital angular momenta.

Essentially new data on nuclear forces can be obtained from nucleon scattering by nucleons at energies of several hundreds of Mev, when the wavelength of the incident particle becomes much smaller than the radius of action of the nuclear forces ($\lambda < \hbar/\mu c = 1.4 \cdot 10^{-13}$ cm). It then becomes possible to measure the deepest lying regions of the nucleon force field. In order to investigate the influence of spin-dependent forces on the scattering, it is necessary that in addition to experimenting with unpolarized particle beams one study also the scattering of polarized nucleon beams by nucleons.

It should be emphasized that the methods used in the theoretical analysis of the experimental data obtained for low energies are completely invalid for the new energy region. For this reason, and also partly because of the absence of a rigorous theory of nuclear forces, the consequences of the hypothesis of charge invariance are found to be quite useful. The use of the isotopic spin concept allows one to make some progress in the analysis of the results of experiments with high-energy particles and to exhibit some new regularities in the nuclear interaction of nucleons [30]. This concept makes it possible to separate the set of all possible states of two nucleons in a high-energy collision into two groups whose total isotopic spin is either $T = 1$ or $T = 0$, and to study the interaction in these two groups separately. Data on the interaction of two nucleons in states with $T = 1$ can be obtained by studying the interaction of any pair of nucleons (p-p, n-n, or n-p), whereas the interaction for $T = 0$ requires experiments with different nucleons (n-p).

Due to the great basic importance of nucleon-nucleon scattering experiments, they were performed on a wide front in the Laboratory for Nuclear Problems beginning in the spring of 1950. Experiments were performed with nucleons whose energies ranged from 380 to 660 Mev, an energy range which had not previously been studied.

Elastic Proton-Proton Scattering and Polarization by this Process

In experiments performed by E. Segre, O. Chamberlain, and others in the USA in 1949, it was established

that in the energy range from 150 to 340 Mev the elastic proton-proton scattering cross section is independent of angle and energy. This would be an indication of a very strong nuclear interaction between two protons at energies of the order of hundreds of Mev.

Investigations of this phenomenon started on our synchrocyclotron in 1952 at proton energies from 460 to 660 Mev [31-33]. These experiments gave the first indication of a sharp anisotropy in high-energy proton-proton scattering, as well as the increase of the differential cross section as the scattering angle is decreased. Analogous results were obtained by a second group of investigators [34, 35], who used a different method.

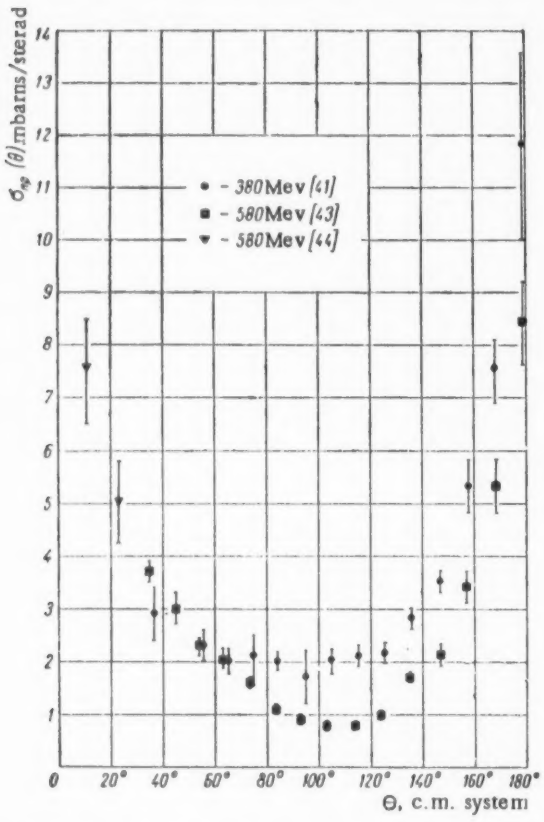

Fig. 7. Elastic scattering of neutrons by protons at 380 and 580 Mev. Analysis of the 580 Mev data indicates that a state with orbital angular momenta $l \sim 5$ contributes to the scattering. The sharp increase of the (n-p)-scattering cross section in the small-angle region at 580 Mev would seem to be due to the increased probability for inelastic processes (meson production) in the energy interval from 380 to 590 Mev, which gives the scattering a diffraction character.

The data obtained in all these experiments [31-35] for three incident proton energies is shown in Figure 4. In addition to the strong anisotropy, one should note the constancy of the proton-proton elastic scattering total cross section in the energy interval studied [31, 33].

In order to obtain a unique phase analysis of the experimental data on elastic nucleon scattering, in addition to results from unpolarized nucleon scattering one must have data on polarized particle scattering. Figure 5 shows the results of an investigation of the angular distribution of the polarization [36] which results from elastic 635 Mev proton-proton scattering.

Elastic Neutron-Neutron Scattering

By the use of an original method developed in our Laboratory in 1952 and 1955-1956 [37, 38], data was first obtained on neutron-neutron scattering. Measurements of the elastic differential cross sections for neutron-neutron scatterings were performed at neutron energies from 300 to 590 Mev.

It was found that (within experimental accuracy) the differential cross sections for (n-n)- and (p-p)-scattering are equal for equal nucleon energies over the whole range of scattering angles studied (Figure 6). It was also found that the total (n-n)- and (p-p)-interaction cross sections were equal [39, 40]. This result verifies most directly the charge-independence hypothesis of nuclear forces in the high-energy region, and allows one to consider all the fundamental conclusions with respect to the nuclear interaction of two protons to be valid also for that of two neutrons.

Elastic Neutron-Proton Scattering

The principal importance of experiments on neutron scattering by protons consists of the fact that this data can be used to obtain information on the nuclear interaction between unlike nucleons. The first experiments on the scattering of high-energy neutrons by protons, performed by E. Segre and others in 1948 in Berkeley using 40 and 90 Mev neutrons, showed that there is an intense backward scattering of the neutrons (in the center-of-mass system). These experiments were thus a direct proof of the fact that the nuclear forces between neutrons and protons have an exchange character.

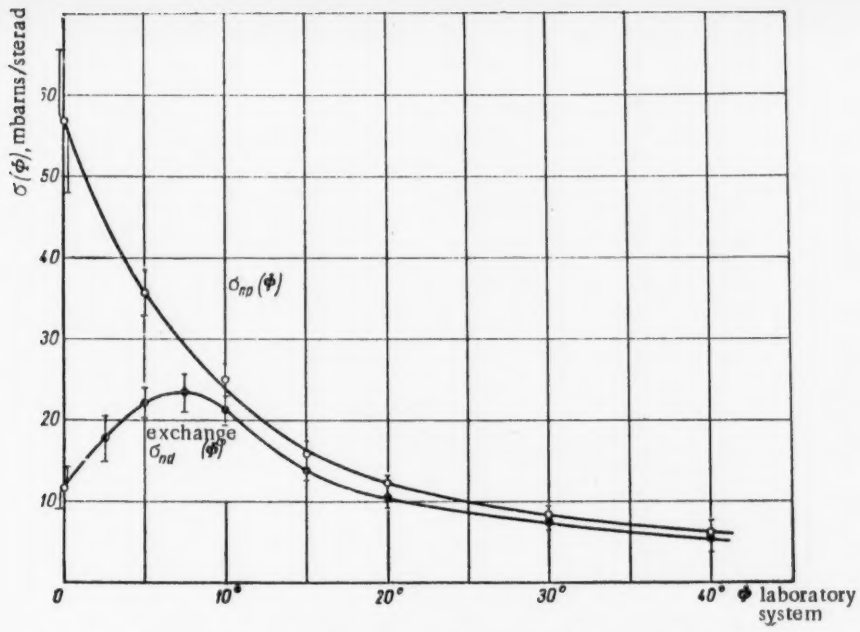

Fig. 8. Exchange scattering of neutrons by protons and deuterons at 380 Mev.

Neutron scattering by protons was studied systematically on our synchrocyclotron in the neutron energy range from 380 to 580 Mev [41-44]. The results of these investigations are shown in Figure 7.

Experiments on 380 Mev neutrons performed in 1950-1951 show that the differential (n-p)-scattering cross section hardly changes in a wide range of angles in the neighborhood of 90°, and is relatively large. This made it possible to conclude that at high energies the interaction in the neutron-proton system is very strong, as is true also for the proton-proton system. Thus, on the basis of nucleon scattering experiments it was established that at high energies the nuclear interaction is very strong for arbitrary pairs of nucleons.

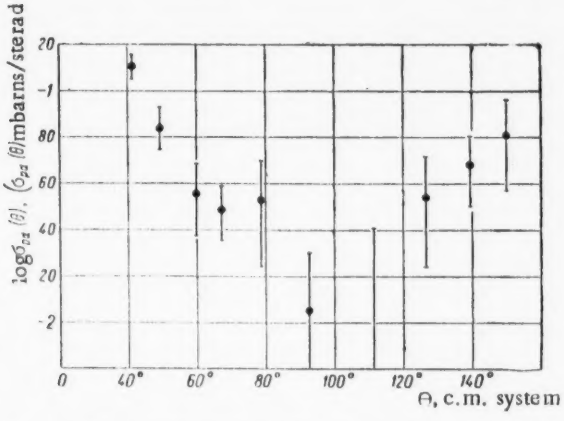

Fig. 9. Elastic scattering of protons by deuterons at 660 Mev. The total elastic (p-d) scattering cross section at this energy is about 2-3% of the total (p-d) interaction cross section.

Experiments at 580 Mev [43-44] show, as do those at 380 Mev, that in this energy region the exchange character of the nuclear interaction between neutrons and protons is clearly expressed, and that the contribution of exchange forces to the nucleon interaction remains large up to 600 Mev.

It should be noted that none of the present experimental data on high-energy elastic nucleon-nucleon scattering is in contradiction to the hypothesis of the charge invariance of nuclear forces. Analysis of the data on nuclear scattering [30, 42] in terms of concepts which lie at the basis of this hypothesis indicate the sharp difference in the variation of the angular and energy dependences of the nucleon interaction cross section for states with different isotopic spins ($T = 0$ and $T = 1$), and thus indicate the difference in the nucleon interactions in these states.

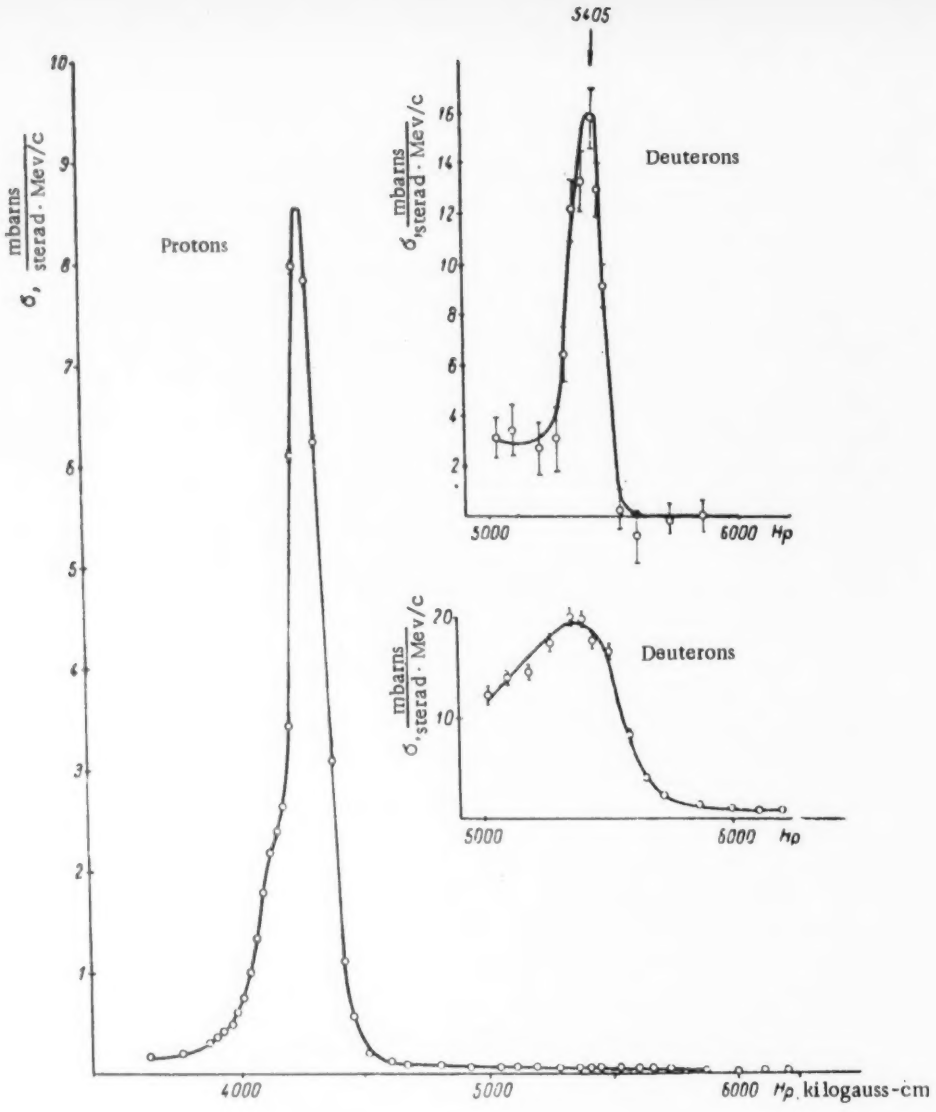

Fig. 10. Pulse spectrum of protons and deuterons emitted from lithium at an angle of 7.6° to the incident 675 Mev proton beam. The deuterons are emitted as a result of collisions of the incident protons with the quasi-deuteron groups within the lithium nuclei. At the upper right is the pulse spectrum of deuterons from elastic (p-d) collisions at the same angle of observation and the same incident proton energy.

Exchange Scattering of Neutrons by Deuterons at 380 Mev

The results of all experiments on the scattering of unpolarized neutrons by protons, which indicates the large role played in the nucleon interaction by exchange forces, could not be used to reach any conclusions on the spin dependence of these forces. Pomeranchuk [45] suggested an original method for answering this question, by comparing experimental data on fast protons obtained from exchange collisions of high-energy neutrons with deuterons and with free protons.

In an experiment of this type [46] it was found that for low scattering angles the cross section for emission of high-energy protons in exchange scattering of neutrons by deuterons is much lower than the cross section for

neutron scattering by free protons (Figure 8). This fact pointed to the conclusion that in exchange (n-p) collisions simultaneous spin exchange may occur with significant probability. In other words, the contributions of the spin-exchange and the spin-nonexchange forces to the neutron-proton exchange interaction are of the same order of magnitude.

Elastic Scattering of Protons by Deuterons and Knockout of Deuterons from Light Nuclei by Protons

It had already been established in 1952 [47] that the elastic scattering through large angles of 460 Mev protons by deuterons is accompanied by the transfer of 300 Mev to the deuteron. The most complete data on the angular dependence of the (p-d) differential scattering cross section was obtained with 660 Mev protons [48] (Figure 9). Of particular interest is the scattering of protons through angles of the order of 130-150° (in the center-of-mass system) which was found in this experiment, when the deuteron, moving as a whole in the forward direction, is given an energy of 500-600 Mev which is of the order of hundreds of times the deuteron binding energy. The interpretation of the observed facts requires the consideration of a collective three-particle mechanism of nucleon interaction.

In order to study the collision of high-energy protons with quasi-deuteron groups in nucleons, special experiments were performed on the six-meter synchrocyclotron.

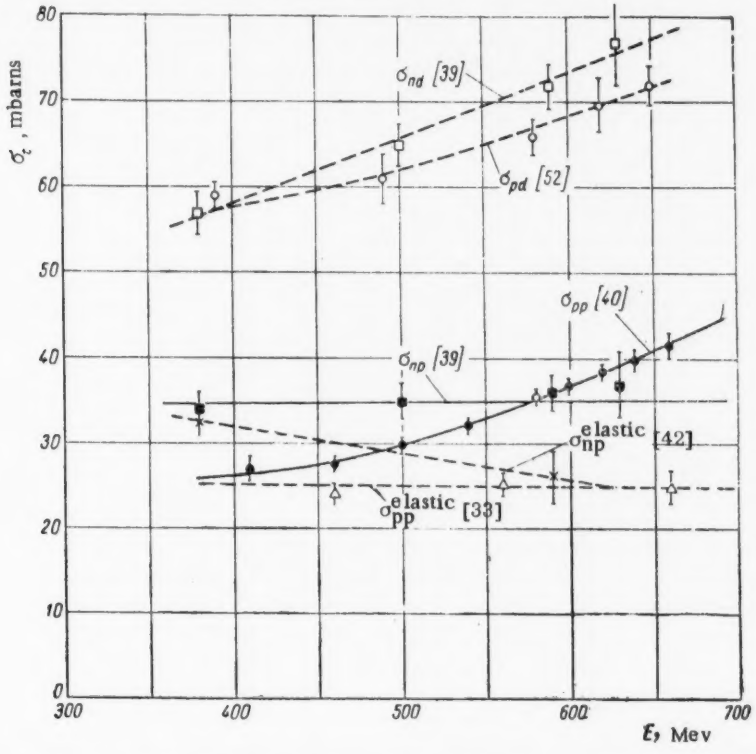

Fig. 11. The energy dependence of the total interaction cross sections for nucleons with nucleons and with deuterons, as well as the total elastic (n-p) and (p-p) scattering cross sections.

Light nuclei were bombarded by 675 Mev protons [49], and the emission of deuterons with energies of the order of 600 Mev was observed in the forward direction at small angles with respect to the incident proton beam; this is similar to the elastic (p-d) collisions observed at the same particle energies and angle of observation in the same experiments (Figure 10).

The observed phenomenon can be given a qualitative explanation based on concepts of the existence of short-lived strongly interacting groups of nucleons in nuclei [50], or by using the predictions of the high-momen-

tum model of the nucleus as developed recently by K. Brueckner.

All these experiments, together with those (e.g. [51]) in which high-energy particles were observed to cause the emission of heavy fragments (tritium, helium, lithium, berrylium, etc.) at energies higher than the potential barrier, indicate directions for the investigation of other than two-body forces between the nucleons in nuclei.

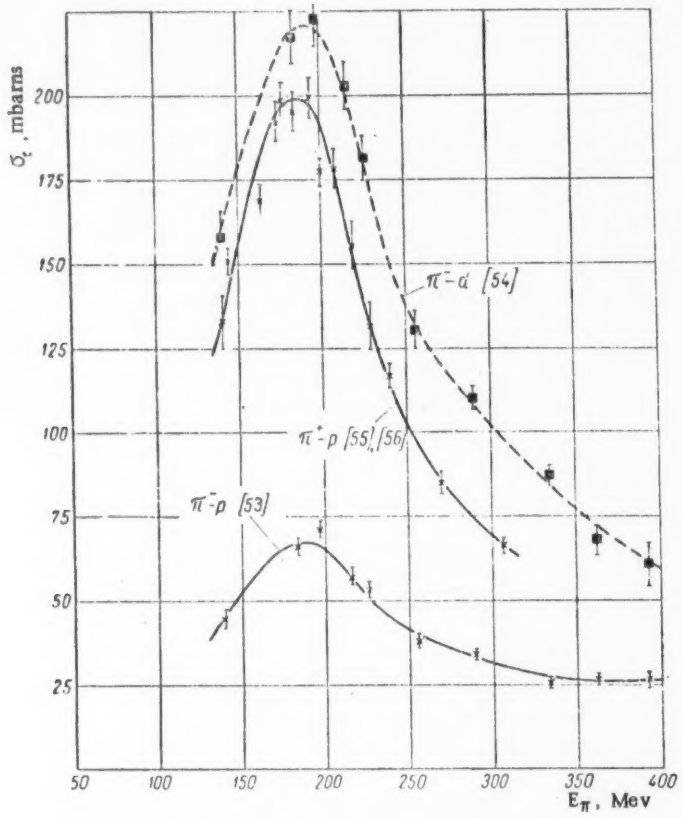

Fig. 12. Total cross section for the interaction of π^+- and π^--mesons with hydrogen and deuterium. The "resonance" behavior of the cross sections is in the vicinity of 190 Mev characterizes the meson-nucleon interaction in the state with isotopic spin and total angular momenta 3/2. At an energy of $E_{lab} \geq 300$ Mev the contribution to scattering from the state with isotopic spin 1/2 becomes significant.

Total Cross Section of the Nuclear Interaction of Nucleons with Other Nucleons and with Deuterons

Figure 11 shows the results of fundamental experiments, performed on the six-meter synchrocyclotron by various investigators [33, 39, 40, 42, 52], related to the determination of the total cross section for the nuclear interaction and for elastic scattering of nucleons. The data obtained leads to the following conclusions:

1. In the energy region studied from 380 to 660 Mev the cross section for meson production in collisions of like and unlike nucleons increases sharply.

2. The total elastic nucleon-nucleon scattering cross sections for states with different isotopic spins depended differently on the energy, just as was found for lower energies: for $T = 1$ the elastic nucleon scattering cross section remains constant, and for $T = 0$ it decreases with increasing energy [42]. This may indicate the decrease of the total strength of the nucleon interaction for states with $T = 0$ as the energy is increased.

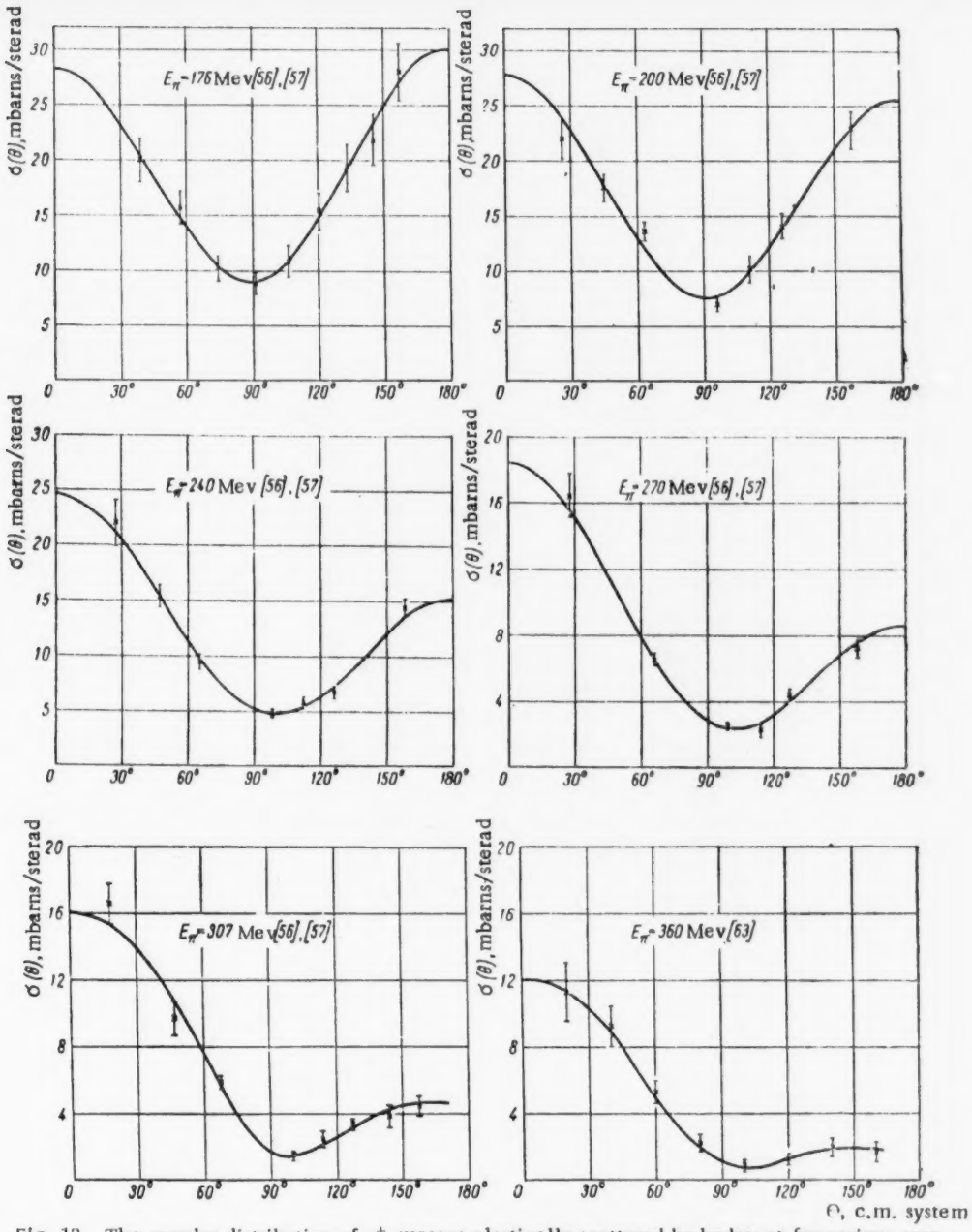

Fig. 13. The angular distribution of π^+-mesons elastically scattered by hydrogen for various energies. It is seen from the figure that close to the "resonance" energy (190 Mev) the angular distribution is symmetric about 90°. At energies greater than the "resonance" energy, forward scattering predominates.

In summing up the results of experiments on elastic scattering of nucleons by nucleons and by deuterons, one may say that they give some idea as to the principal features of the nucleon-nucleon interaction in the energy region investigated (up to 700 Mev):

1. At high energies the nucleon interaction involves very strong forces of various types, namely central forces,

tensor forces, and exchange forces which depend in a complicated way on the spin.

2. The contributions to the nuclear interaction of nucleons from the different kinds of forces are comparable.

3. The nucleon interaction is charge independent.

It cannot be doubted that these experimental facts must be a practical criterion for any future theory of nuclear forces.

Interaction of Mesons and Nucleons

The problem of nuclear forces cannot be entirely separated from the study of the properties of all other elementary particles. It is known that there is a relation between elementary particles and fields of force. For instance, the interaction between charged particles takes place through photons, which are the quanta of the electromagnetic field. Therefore, the properties of photons are strongly related to the characteristics of the electromagnetic forces between charged particles.

Similarly, the properties of π-mesons are intimately related to the forces between nuclei, as has already been established, which means that they are related to nuclear forces. The importance of the π-meson properties in elementary particle physics can thus be understood.

Meson theory, that is the formal theory of meson fields, is based on the hypothesis, first formulated by H. Yukawa, that nuclear forces are caused by mesons. Although this concept is correct, meson theory is still, unfortunately, in the early stages of its development.

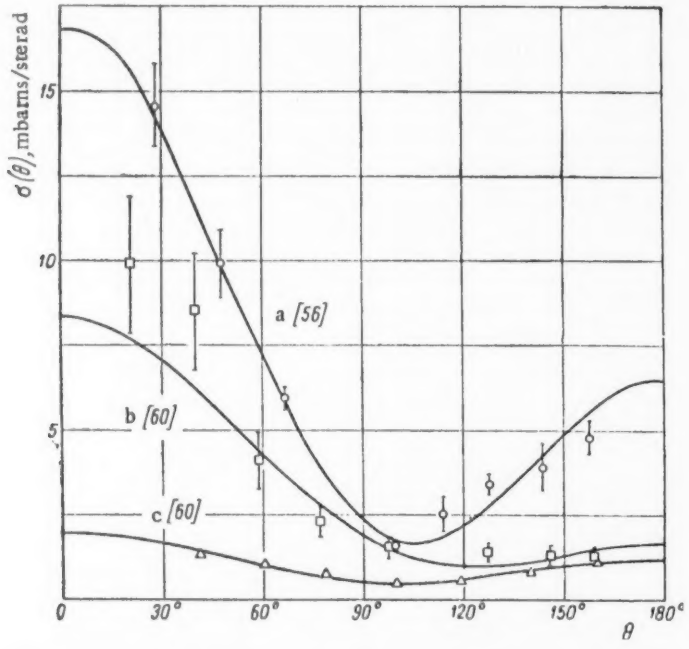

Fig. 14. Scattering of π-mesons by hydrogen at 307 Mev in the following processes: a) $\pi^+ + p \rightarrow \pi^+ + p$; b) $\pi^- + p \rightarrow \pi^0 + n \rightarrow \gamma + \gamma + n$; c) $\pi^- + p \rightarrow \pi^- + p$. From the data given in this figure and in Fig. 13, one can obtain the coupling constant f^2 of the meson-nucleon interaction, which is found to be about 0.1.

At the present time, when any specific form of meson theory gives, at best, only qualitative agreement with experiment, a fundamental problem of experimental high-energy physics is that of obtaining data for the phenomenological description of the interaction of various particles. In the absence of an over-all view joining the

various phenomena of elementary particle physics, it is impossible to construct a consistant meson theory. Thus, the phenomenological description of particle interactions, particularly for π-mesons and nucleons, is the first step in formulating a meson theory of nuclear forces.

Both in the USSR and in foreign countries many paths have been taken in investigations which could be used to obtain various features of the over-all picture of particle interactions: in addition to nucleon-nucleon scattering at various energies and scattering angles, meson scattering by nucleons has been studied, as well as meson production on nucleons by nucleons, mesons and γ-rays.

Scattering of π-Mesons by Nucleons and Complex Nuclei

A large forward step in the investigation of the π-meson properties was made between 1950 and 1954 in the classical measurements of their parities and spins by W. Panofsky and J. Steinberger, as well as the total and differential cross sections for scattering π-mesons by nucleons for energies up to about 200 Mev measured by E. Fermi and others. Investigations of meson scattering by nucleons started in our Laboratory in 1954 after we had obtained well-collimated π-meson beams [6]. The investigations attempted to obtain data in the π-meson energy range above 200 Mev, for which there was as yet practically no data.

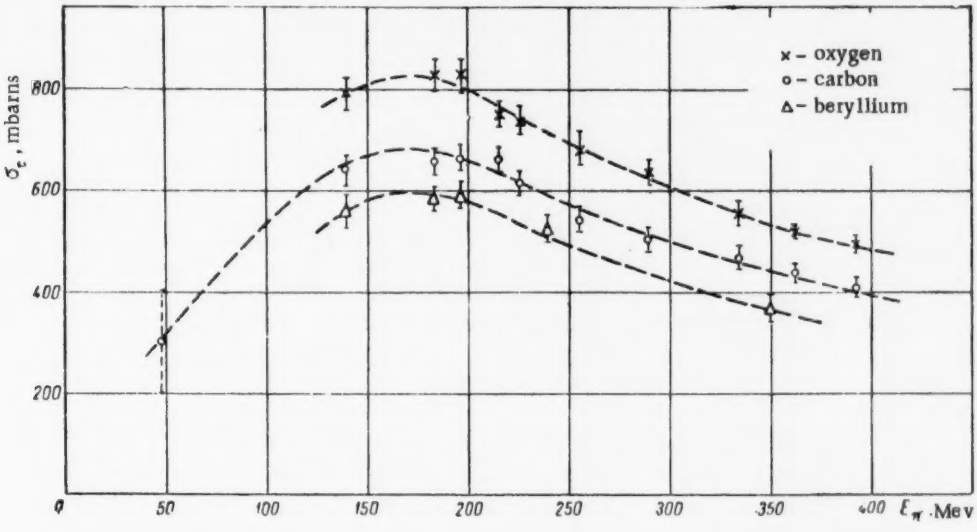

Fig. 15. The energy dependence of the total cross section for the interaction of π-mesons with light nuclei [65]. The curves are reminiscent of the energy dependence of the cross section for the total interaction of π^+- and π^--mesons with nucleons. Analysis shows [66] that the interaction of π-mesons with nuclei takes place primarily by means of interactions with individual nucleons of the nucleus.

Several experiments were devoted to the study of the energy dependence of the total interaction cross sections for π^+- and π^--mesons with hydrogen and deuterium in the energy range from 140 to 400 Mev [53-56] (Figure 12), and to investigations of angular distributions of π-mesons scattered by hydrogen in the $\pi^+ + p \rightarrow \pi^+ + p$, $\pi^- + p \rightarrow \pi^- + p$, and $\pi^- + p \rightarrow \pi^0 + n$ reactions for the following meson energies: 176, 200, 240, 270 [56, 57], 307 [58-61], 330 [62] and 360 Mev [63].

Some of the data obtained is shown in Figures 13 and 14. Experiments on the angular distribution of π-mesons scattered by hydrogen were performed with the aid of scintillation counters and by means of photographic plates.

All the data obtained, in particular the equality of the cross section for the interaction of both π^+ and π^--mesons with deuterium, verifies the principle of charge symmetry for a set of mesons and nucleons, as well as the more rigorous principle of charge independence. Although the principle of charge independence fits naturally

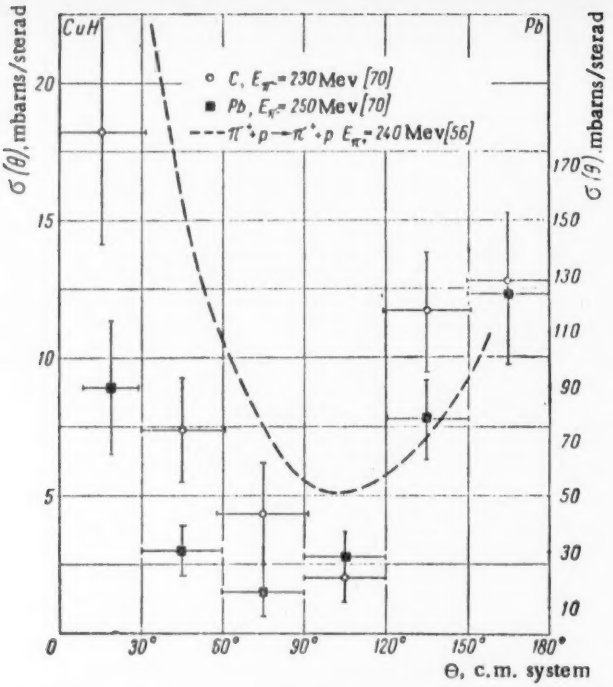

Fig. 16. Inelastic scattering of π^--mesons by carbon and lead nuclei. Analysis of the results shows that there is a correlation between the energy drop and the π-meson scattering angle, which indicates that inelastic π-meson scattering in the energy interval from 60-180° is due primarily to single scattering of π-mesons by separate nucleons in the nuclei. The dotted curve, which gives the differential cross section for elastic scattering of 240 Mev π-mesons by hydrogen, is included for comparison.

into the meson theory of nuclear forces, it must be emphasized that conclusions as to the validity of this principle were obtained, without using the meson theory, by a phenomenological investigation of the data on meson scattering by nucleons and the data presented below on the production of mesons by nucleons.

Experiments verified the fact that in the energy range up to 300 Mev the meson-nucleon interaction is extremely strong for the state whose isotopic spin and total angular momentum are 3/2. The scattering cross section in this state attains its maximum possible value at a π-meson energy of about 190 Mev. It is therefore often said that the meson-nucleon interaction has a "resonant" character. It is possible that this resonance is related to the nucleon structure [64], although one may not assert this at present. Investigations of the meson-nucleon interaction in the high-energy region led to the conclusion [53, 55] that the contribution of the state with isotopic spin 1/2 to the scattering becomes significant for $E_\pi \geq 300$ Mev.

The high accuracy with which the angular distributions of π^+-meson scattering by hydrogen have been measured for energies higher than 200 Mev allowed the first phase analysis accounting not only for the s- and p-states, but also for the d-state. It follows from the analysis [57] that the meson-nucleon interaction radius is about $7 \cdot 10^{-14}$ cm.

All the data obtained on our synchrotron [56, 57, 59, 60, 62, 63] are consistent with a coupling constant f^2 whose value is about 0.1.

The interaction of mesons with complex nuclei has been the subject of several works using very different experimental methods: scintillation counters [65-67], photographic plates [68, 69], cloud chambers [70], and dif-

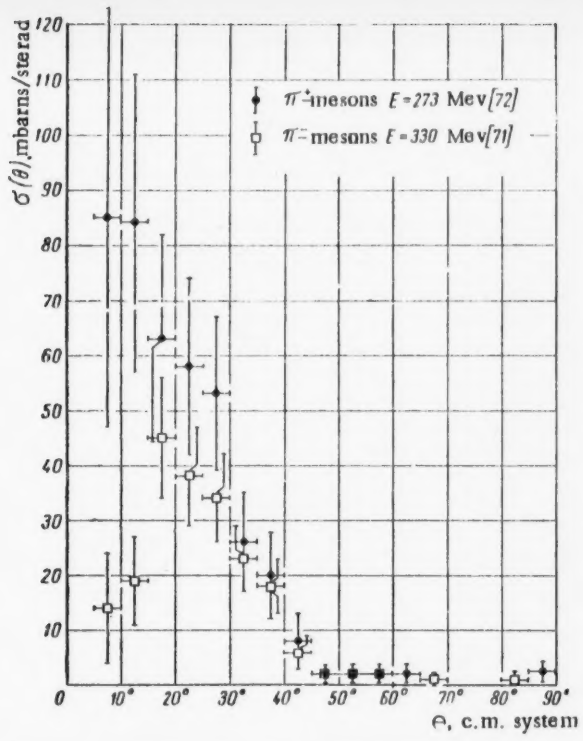

Fig. 17. Elastic scattering of π^+- and π^--mesons by helium nuclei. The entirely different behavior of the differential elastic scattering cross section for small angles is quite evident. This is due to the different signs of the interference terms from the Coulomb and nuclear interactions for π^+- and π^--mesons.

fusion chambers [71, 72]. Some of the data obtained is shown in Figures 15-17.

Data on the inelastic scattering of π-mesons by nuclei in photographic emulsions [69] shows that there are attractive forces between nuclei and 160 Mev π-mesons, and that the depth of the corresponding potential well is about 25 Mev.

Production of Mesons by Nucleons

Early experiments. A large number of experiments on the synchrocyclotron was devoted to the production of single charged or neutral π-mesons by the collision of nucleons. It is clear that from the theoretical point of view the production of charged mesons in nucleon-nucleon collisions is more complex than meson scattering by nucleons.

In order to form a sufficiently detailed picture of the phenomenon of meson production in nucleon-nucleon collisions, various methods were used to study the qualitative and quantitative aspects of these processes.

In such collisions π-mesons may be produced by any of the following processes:

$$\begin{array}{l|l} p + p \to \pi^0 + p + p & n + n \to \pi^0 + n + n \\ p + p \to \pi^+ + p + n & n + n \to \pi^- + p + n \\ p + p \to \pi^+ + d & n + n \to \pi^- + d \end{array}$$

$$\begin{array}{l} n + p \to \pi^+ + n + n \\ n + p \to \pi^- + p + p \\ n + p \to \pi^0 + n + p \\ n + p \to \pi^0 + d \end{array}$$

Between 1951 and 1952 the five-meter instrument was used to obtain data on the production of π^0-mesons in (n-p)- and (n-n)-collisions [73] with 400 Mev neutrons, as well as in the $p\text{-}p \to \pi^0 + p + p$ [74-76] and $p + p \to \pi^+ + d$ [77] processes with 460 Mev protons. In addition, π^0-meson production was studied in collisions of protons [78, 79] and neutrons [80] with complex nuclei.

These experiments led to the following results:

1. Difficult and accurate measurements of the γ-ray spectra from the decay of π^0-mesons formed by bombarding complex nuclei by 460 Mev protons led to the conclusion that mesons are produced primarily in the p-state [78, 79].

2. Measurements of the probability for producing π^0-mesons on nuclei of different atomic weights made it possible to evaluate [73, 74] the mean free path of mesons in nuclear matter.

3. The first experiments were performed to investigate the production of π^0-mesons by collisions of neutrons with nucleons and complex nuclei [81].

4. It was shown [73] that near the threshold for meson production the production of π^0-mesons is forbidden in neutron-neutron collisions, as was found (in experiments conducted at Berkeley) for proton-proton collisions. This resemblance of the (n-n)- and (p-p)-interactions indicates the validity of the hypothesis of charge symmetry for systems consisting of nucleons and mesons.

5. Experiments on the production of π^0-mesons in (n-p)- and (n-n)-collisions [73] led to the following qual-

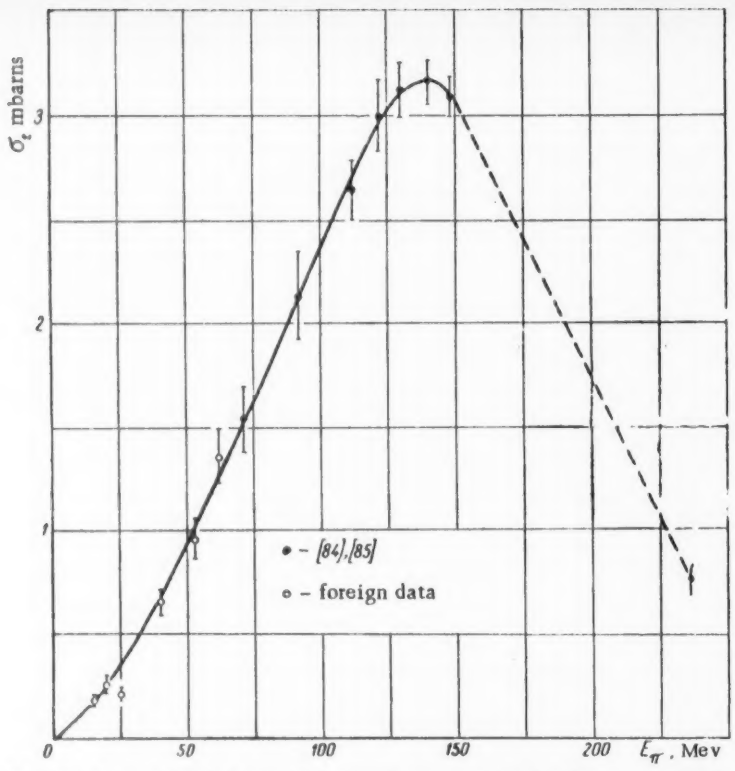

Fig. 18. Energy dependence of the total cross section for the $p + p \rightarrow \pi^+ + d$ reaction. E_π is the kinetic energy of the meson produced in the center-of-mass system. Of interest is the maximum, which is due to the strong "resonance" interaction of the meson and nucleon in the state whose isotopic spin and total angular momentum is 3/2.

itative description of π-meson production near threshold:

Processes with high probability are

$$p + p \rightarrow \pi^+$$
$$n + n \rightarrow \pi^-$$
$$n + p \rightarrow \pi^0$$

Processes with small probability are

$$p + p \rightarrow \pi^0$$
$$n + n \rightarrow \pi^0$$
$$p + n \rightarrow \begin{cases} \pi^+ \\ \pi^- \end{cases}$$

It was shown for the first time [82] that the low probability for formation of charged mesons in (n-p)-collisions is due to the fact that the meson-nucleon interaction is particularly strong in states whose isotopic spin and angular momentum are 3/2, states which are very likely to occur in experiments on the interaction of π-mesons with nucleons.

6. In bombarding hydrogen by 460 Mev protons it was shown [74-76], in agreement with the data obtained by G. Marshall and co-workers at Chicago, that as the energy is increased the $p + p \rightarrow \pi^0 + p + p$ reaction becomes less forbidden. A similar result stating that the production of π^0-mesons by (n-n)-collisions is no longer forbidden at high energies was obtained later [83], after the synchrocyclotron was reconstructed and a 580 Mev neutron beam was obtained.

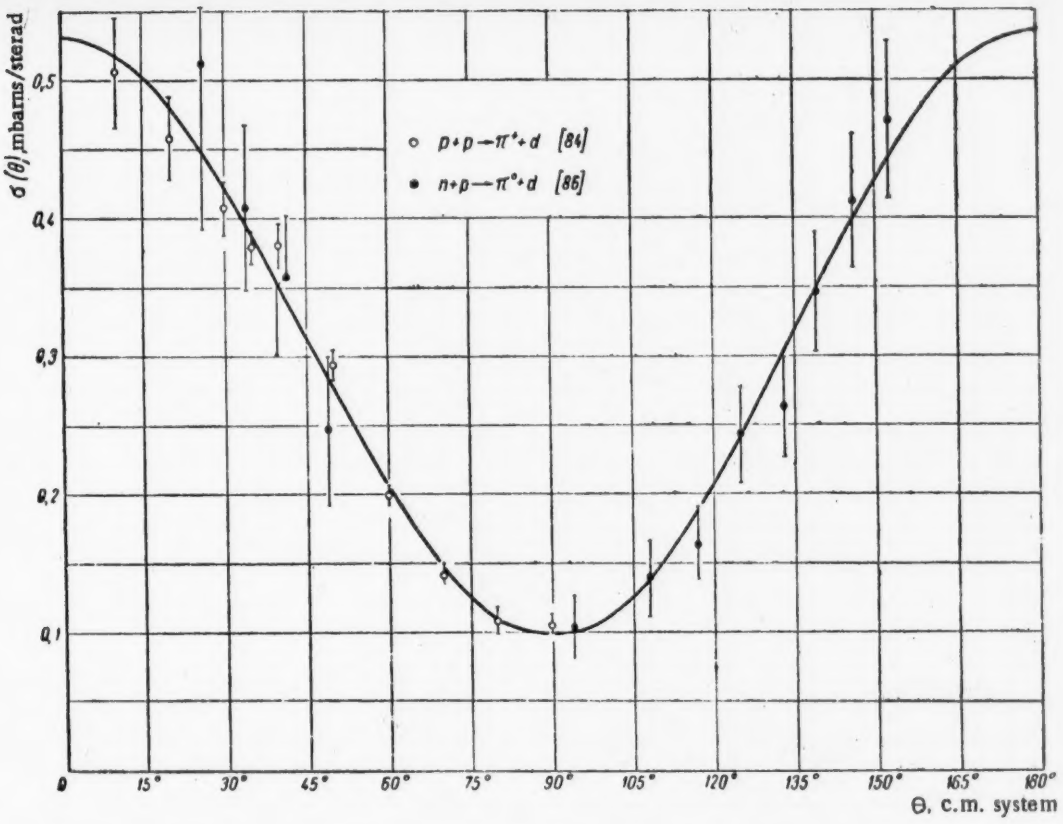

Fig. 19. The angular distribution of π-mesons emitted in the $p + p \rightarrow \pi^+ + d$ and $n + p \rightarrow \pi^0 + d$ reactions with an incident proton energy of 650 Mev and an incident neutron energy of 600 Mev. The data for the second reaction is given in relative units. The similar behavior of the differential cross sections for both reactions is a consequence of the charge independence of elementary particle interactions, so that this data verifies this independence.

7. The $p + p \rightarrow \pi^+ + d$ reaction was investigated similarly [77] for a proton energy of 460 Mev. The angular distribution obtained showed that in this reaction mesons are produced primarily in the p-state, and that effects related to meson emission in the d-state are insignificant.

Energy dependence of the meson-production cross sections and meson angular distributions. All the meson-production processes mentioned above were investigated directly or indirectly after the 680 Mev proton beam was obtained on the synchrocyclotron.

Experiments studying the production of π^+-mesons by bombarding protons by protons with energies from 460 to 660 Mev [84] established for the first time that there is a resonance in the cross section for the $p + p \rightarrow \pi^+ + d$ reaction (Figure 18). From an analysis of the angular distribution of the mesons emitted in this reaction (Figure 19) it follows that in this energy region the mesons are produced primarily in the p-state. This conclusion was obtained also from an experimental investigation [86] of the angular distribution of π^0-mesons produced in the $n + p \rightarrow \pi^0 + d$ reaction with 600 Mev neutrons (Figure 19). From the point of view of isotopic invariance this reaction is identical with $p + p \rightarrow \pi^+ + d$. In addition to the two-particle reaction in proton-proton collisions, the $p + p \rightarrow \pi^+ + n + p$ reaction was investigated with 657 Mev protons (Figure 20) [87].

The production of π^0-mesons was investigated by bombarding protons and deuterons by protons [88-91] and neutrons [83, 92] for energies up to 680 Mev.

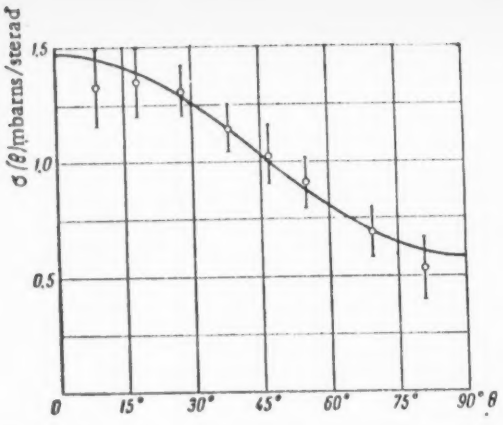

Fig. 20. Angular distribution of π^+-mesons from the $p + p \rightarrow \pi^+ + p + n$ reaction, with an incident proton energy of 657 Mev.

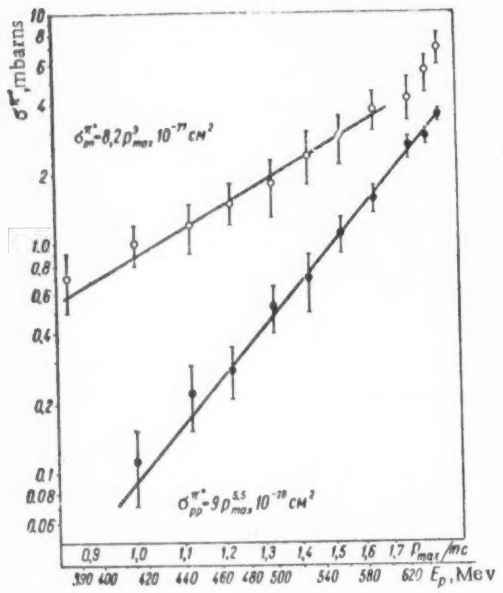

Fig. 21. Energy dependence of the total π^0-meson production cross sections in (p-p)- and (p-n)-collisions. E_p is the proton energy, and p_{max} is the maximum momentum of the π^0-mesons in the center-of-mass system, given in units of mc. As is seen from the figure, $\sigma_{pp}^{\pi^0}$ increases with proton energy much more rapidly than does $\sigma_{pn}^{\pi^0}$, due to the fact that production of π^0-mesons is "forbidden" in (p-p)-collisions close to threshold.

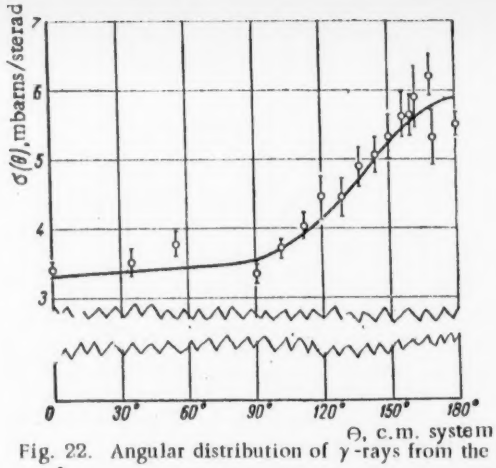

Fig. 22. Angular distribution of γ-rays from the decay of π^0-mesons produced by 660 Mev protons incident on carbon. θ is the effective angle in the center-of-mass coordinate system of the colliding nucleons. The decrease in the γ-ray intensity at small angles is due to the fact that the nucleus is a "thick" absorber both for the π^0-mesons and the incident nucleons.

At 660 Mev the cross section ratio $\sigma_{np}^{\pi^0}/\sigma_{pp}^{\pi^0}$ is almost equal to two [88, 90], as predicated by the hypothesis of charge invariance for the case in which the meson-nucleon system has a final state with isotopic spin 3/2 [93].

The energy dependence of the π^0-meson production cross section for protons incident on protons or deuterons was investigated both with the internal [89, 94] and external [90, 91] proton beams. Figure 21 shows the results of the best measurements. The data gives an energy dependence for the total π^0-meson production cross section in (p-p)-collisions [89] which is entirely different from that previously assumed.

The angular distribution of π^0-mesons produced in nucleon-nucleon collisions was studied at energies of 445, 500, 555, and 660 Mev [88, 89, 93]. It was found that the angular distribution becomes practically isotropic when the energy is increased to 660 Mev, although it is anisotropic at low energies. This would seem to be due to the fact that in the neighborhood of 600 Mev there begins to occur a strong interaction between the π^0-meson and one of the nucleons in the final state.

In studying the angular distribution of γ-rays from the decay of π^0-meson produced on nuclei, an interesting asymmetry was found [88, 90, 94] (Figure 22) which arises because the mean free path of mesons and protons in nuclear matter is small compared to the dimensions of the nucleus. Data on the absorption of mesons in nuclear matter was obtained also by measuring the π^0-meson yield from various nuclei when they are bombarded by protons [88] or neutrons [80, 83].

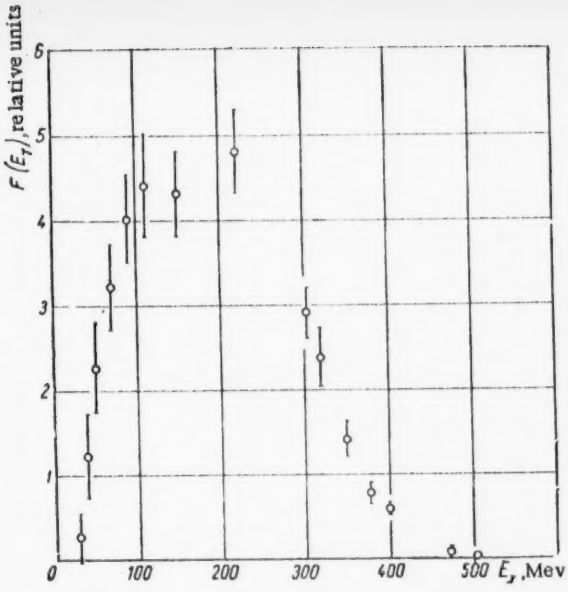

Fig. 23. Energy spectrum of γ-rays at an angle of 0° from the decay of π^0-mesons produced in (p-p)-collisions at 660 Mev. This spectrum characterizes the angular and energy distributions of the π^0-mesons, which cannot be observed directly due to the short lifetime of the π^0-meson ($\tau < 10^{-15}$ sec).

Energy spectra of particles emitted in inelastic collisions of two nucleons. The spectra of particles emitted in inelastic collisions of nucleons both with other nucleons and with nuclei were investigated by several experimental methods. Among these were the use of a magnetic pair spectrometer to analyze the γ-ray spectra from the decay of π^0-mesons formed in proton-proton collisions [95] (Figure 23) and proton-nucleus collisions [96, 97] (Figure 24), magnetic analysis of secondary protons and deuterons emitted in the collision of two protons [98] (Figure 25), magnetic analysis of charged mesons from (p-p)-collisions [99, 100] (Figure 26) and from proton-nucleus collisions [101, 102] (Figure 27), and the use of photographic plates to analyze the charged-meson spectra from (n-p)-collisions [103] (Figure 28).

Analysis of the γ-ray spectra from the decay of π^0-mesons produced by protons incident on light nuclei shows that as the proton energy increases from 470 to 660 Mev, the energies in the spectrum decrease, as does the anisotropy in the angular distribution of mesons produced in (n-p)-collisions [96]. The reason for this would seem also to lie in the occurrence of a strong interaction between the π^0-mesons and one of the nucleons as the energy is increased. The same method was used to obtain the first data on the angular and energy distributions of π^0-mesons produced in the collision of 660 Mev protons with hydrogen [95].

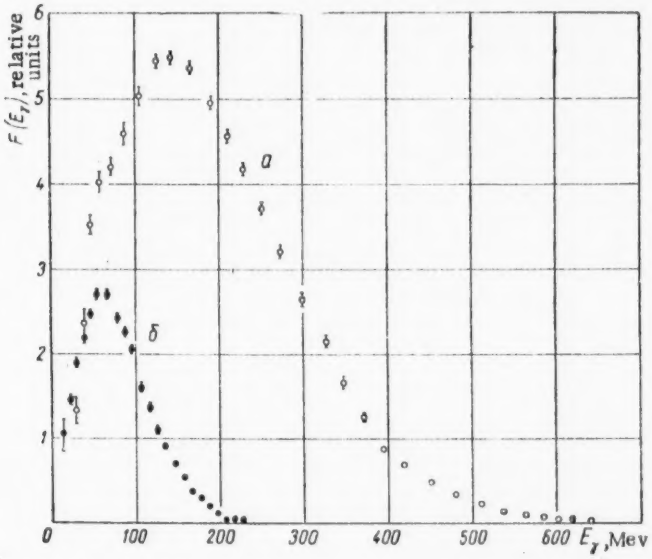

Fig. 24. The energy spectrum of γ-rays from the decay of π^0-mesons produced by 660 Mev protons incident on carbon: a) at an angle of 0°; b) at an angle of 180°. The maximum energy near 600 Mev is caused by those head-on collisions in which one of the two γ-rays produced in the π^0-meson decay obtains practically all the energy.

Fig. 25. Momentum spectrum of secondary particles from (p-p)-collisions in the laboratory coordinate system. The spectrum indicates the presence of the following reactions: 1) elastic (p-p)-scattering (the proton peak at 4250 kgauss · cm); 2) the $p + p \rightarrow \pi^+ + d$ reaction, leading to two deuteron groups at 2880 and 4520 kgauss · cm; 3) the $p + p \rightarrow \pi^+ + p + n$ and $p + p \rightarrow \pi^0 + p + p$ reactions, which give a continuous proton spectrum.

Analysis of the spectra of π^+-mesons produced by 556 and 657 Mev protons in the $p + p \rightarrow \pi^+ + p + n$ reaction shows that in this energy range the matrix element for the reaction is proportional to the meson momentum [99].

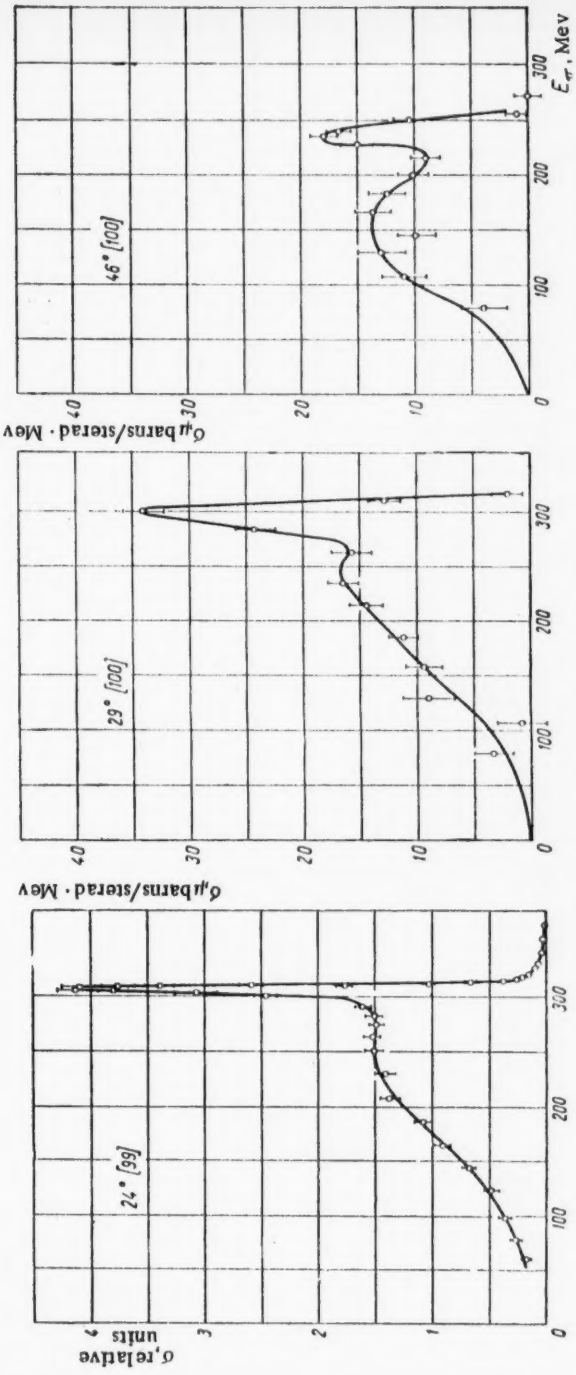

Fig. 26. The energy spectrum of π^+-mesons from the reactions: 1) $p + p \rightarrow \pi^+ + p + n$ and 2) $p + p \rightarrow \pi^+ + d$ at angles of 24°, 29°, and 46° in the laboratory coordinate system with an incident proton energy of 660 Mev. The peak is due to the two-particle reaction (2).

An interesting result was obtained in measuring the emission of charged [102] and neutral [104] mesons by various nuclei when they are bombarded by protons. It was found that the ratio of the number of charged mesons to π^0-mesons was 2 when the protons were incident on nuclei with isotopic spin 0. This again verifies the hypothesis of charge invariance for nuclear forces, both for high and low meson energies.

In conclusion it may be noted that this is the only existing systematic investigation of processes leading to the production of neutral and charged π-mesons.

π-Meson Production by Mesons

It has been known for a relatively long time collisions of π-mesons with nucleons (multiple meson production). This meson production by mesons, however, has until recently been studied only for energies much higher than threshold. An investigation of these processes close to threshold has recently been undertaken in our Laboratory, where meson production by mesons was investigated on liquid hydrogen [105] by means of scintillation counters, and on complex nuclei [106] by means of photographic plates. Figure 29 shows the first data obtained on the energy dependence of the total probability for the $\pi^- + p \rightarrow \pi^0 + \pi^- + p$ and $\pi^- + p \rightarrow \pi^+ + \pi^- + n$ reactions. All attempts to calculate the probabilities of these processes by meson theory have been unsuccessful. From the methodological point of view it is of interest to compare the experimental data with J. Franklin's* calculation based on the Chew-Low theory, which is presented on the same figure. To this date this is by far the best agreement any theory has given with the experimental data.

Conclusion

In summation of all the investigations of the interactions of mesons with nucleons and complex nuclei, as well as of meson production by nucleons on nucleons and on complex nuclei, we may state that they lead to a relatively complete phenomenological picture of the meson-nucleon interaction for energies up to 700 Mev. The fundamental characteristics of this interaction which will have to be accounted for in any future theory are the following:

a) it is charge invariant;

b) it is particularly strong in the state in which the isotopic spin and angular momentum are 3/2.

*Phys. Rev. 105, 1101 (1957).

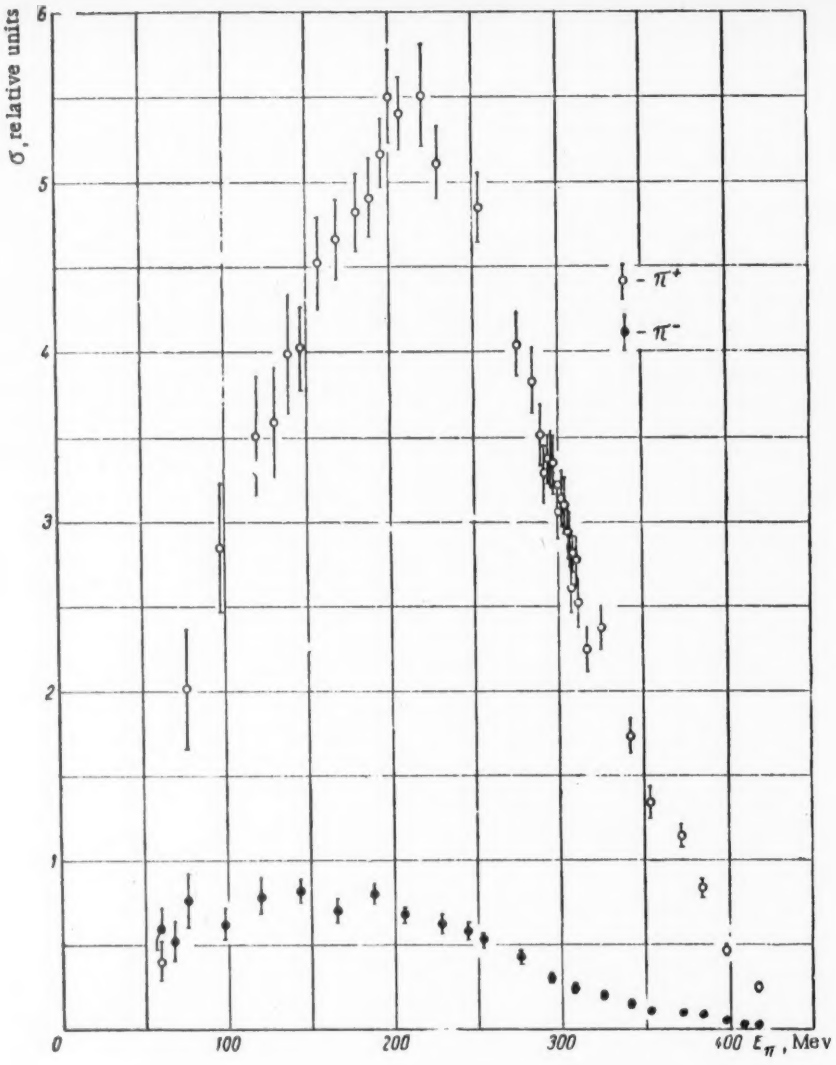

Fig. 27. Energy distribution of π^+- and π^--mesons produced by 660 Mev protons on carbon nuclei at an angle of 24° to the direction of the incident proton beam [101]. The small number of π^--mesons observed is explained by the fact that π^+-mesons may be produced in the nucleus in (p-p)- and (p-n)-collisions, whereas π^--mesons can be produced only in (p-n)-collisions, which are relatively inefficient for charged meson production.

μ-Mesons

It is known that the interaction of μ-mesons with nucleons is much weaker than that of π-mesons. The question remains, however, whether there exist relatively weak nuclear forces due to virtual emission of μ-meson pairs ($\mu^\pm$, μ^0). An attempt to detect a μ^0-meson [107] has shown that if this particle exists it is emitted by nuclei subjected to bombardment by 670 Mev protons with a probability less than or of the order of 10^{-4} times the probability for π-meson emission. Therefore, the contribution to nuclear forces due to the emission of ($\mu^\pm$, μ^0) pairs is insignificant.

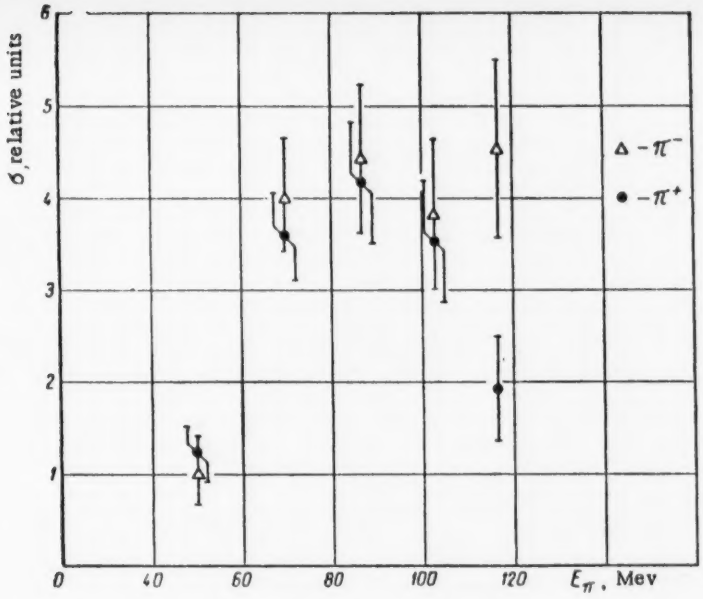

Fig. 28. The spectra of π^+- and π^--mesons produced by 600 Mev neutrons incident on hydrogen. The data is taken at 90°. It is seen that within experimental limits the π^+- and π^--meson yields are equal, which verifies the principle of charge symmetry.

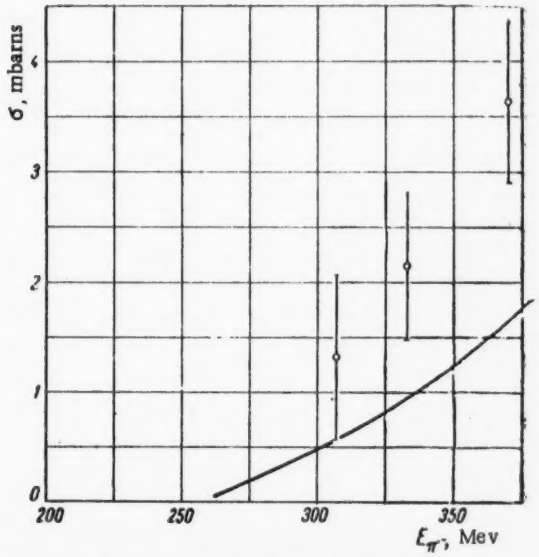

Fig. 29. Cross section for the production of charged mesons on hydrogen by π-mesons close to threshold in the $\pi^- + p \rightarrow \pi^0 + \pi^- + p$ and $\pi^- + p \rightarrow \pi^+ + \pi^- + n$ reactions [105]. The calculated threshold for the production of mesons by mesons on hydrogen is about 170 Mev. The solid line gives Franklin's calculation based on the Chew-Low theory.

Great interest arose in μ-meson decay after the discovery in the USA of the nonconservation of parity in weak interactions. Photographic plates have been used [108] to study the μ-meson decay reaction $\mu^+ \rightarrow e^+ + \nu + \tilde{\nu}$. Of interest was the asymmetry in the angle between the emitted electron and the direction of the μ-meson obtained from the $\pi^+ \rightarrow \mu^+ + \nu$ process. The results obtained verified the conclusion of parity nonconservation, and determined the form of the electron angular distribution with good accuracy.

It is of great interest to compare the data so obtained with Landau's [109] proposed theory of the longitudinal neutrino, according to which the neutrino has vanishing mass and is always polarized along its direction of motion. The energy dependence of the electron asymmetry in the μ^+-decay was determined in difficult experiments with photographic plates. Measurements show that the asymmetry increases with the energy, and the sign of the effect is in agreement with the predictions of the longitudinal neutrino theory. Further experiments are at present being performed on this fundamental problem.

"Strange" Particles

Production of Λ^0-particles has also been studied in our laboratory. Theory, both in the USSR and abroad, has predicted [111] the simultaneous production of a heavy meson and a hyperon. This was later verified by direct experiments on the cosmotron in the USA. The hypothesis that a Λ^0-particle and K-meson are simultaneously produced fails to agree with the nucleon + nucleon $\rightarrow$ nucleon + Λ^0 reaction, but agrees with the nucleon + + nucleon = Λ^0 + Λ^0 reaction.

An attempt was made [112] to observe production of Λ^0-particles by bombarding a target inside the synchrocyclotron by 680 Mev protons, this energy being quite sufficient for the production of two Λ^0-particles. Experiment showed that Λ^0-particles are not produced under these conditions. This is not only an additional and strong argument in favor of the assumption of simultaneous production of a Λ^0-particle and heavy meson, but also led to a conclusion with respect to the isotopic spin of the K^0-meson which participates in the interaction of the Λ^0-particle with a nucleon. It follows from this work that the K^0-meson and its antiparticle $\tilde{K}^0$ are not identical.

The Interaction of High-Energy Particles with Complex Nuclei

It is impossible a priori to tell whether the interaction of π mesons and nucleons with nuclei is given by the sum of the two-body interactions with the separate nucleons in the nucleus. The basic interest in the investigation of the interaction of these particles with nuclei is related to the fact that this can lead to unexpected information on nuclear forces which cannot be obtained from scattering experiments with individual nucleons.

We have already mentioned the large amount of work dealing with the interaction of nucleons and π-mesons with complex nuclei.

In view of the restricted nature of the present article, we cannot give even a brief discussion of all the works in which this interaction has been studied in its various aspects. In order, however, to make it possible for the reader to attain some knowledge of this question, we have given a list of the relevant literature [113-121].

Experimental Method and Apparatus

The extended program of nuclear research performed on the synchrotron with high-energy particles and γ-rays necessitated the development of new methods for recording particles and the design of complex experimental apparatus.

It is impossible within the framework of the present article to describe in any detail most of the delicate and varied experimental apparatus constructed and used during the eight years of research on the synchrocyclotron by various groups of physicists. In speaking, however, of this problem it should be emphasized that from the point of view of difficulty and novelty of the scientific and engineering solutions, as well as from the point of view of the amount of research and development, the design of the necessary methods and apparatus for high-energy experiments is one of the most complex problems that has had to be solved in recent years by physicists and engineers.

In order to give at least a general idea of this aspect of the research and in order to indicate the magnitude of the scientific methodological developments, we shall describe briefly at least some of the apparatus used in the experiments. With this aim in view we include several photographs of typical experimental setups. The total number of such setups was fifty. During the experiments they are usually located along the beam paths in the measuring pavillion (Figure 30), as well as in the meson and polarized-particle laboratories. They were operated by remote control from a special room in which was located the final recording apparatus.

In investigating nucleon and π-meson scattering by nucleons and by nuclei, telescopes of crystal and liquid scintillators were widely used in conjunction with photomultipliers in coincidence circuits whose resolving time was of the order of 10^{-8} sec. Figure 31 shows a typical experiment on π-meson scattering by protons, and Figure 32 is a photograph of a typical setup for measuring nucleon-nucleon scattering. In similar experiments use was made and is being made of high-efficiency hodoscopic systems of several hundred pulse-fed Geiger counters (Figure 33), Čerenkov counters, diffusion chambers up to 400 mm in diameter filled with hydrogen and helium to a pressure of 20 atmos (Figure 34), propane bubble chambers (Figure 35), and a 400 mm diameter cloud chamber in a magnetic field (Figure 36).

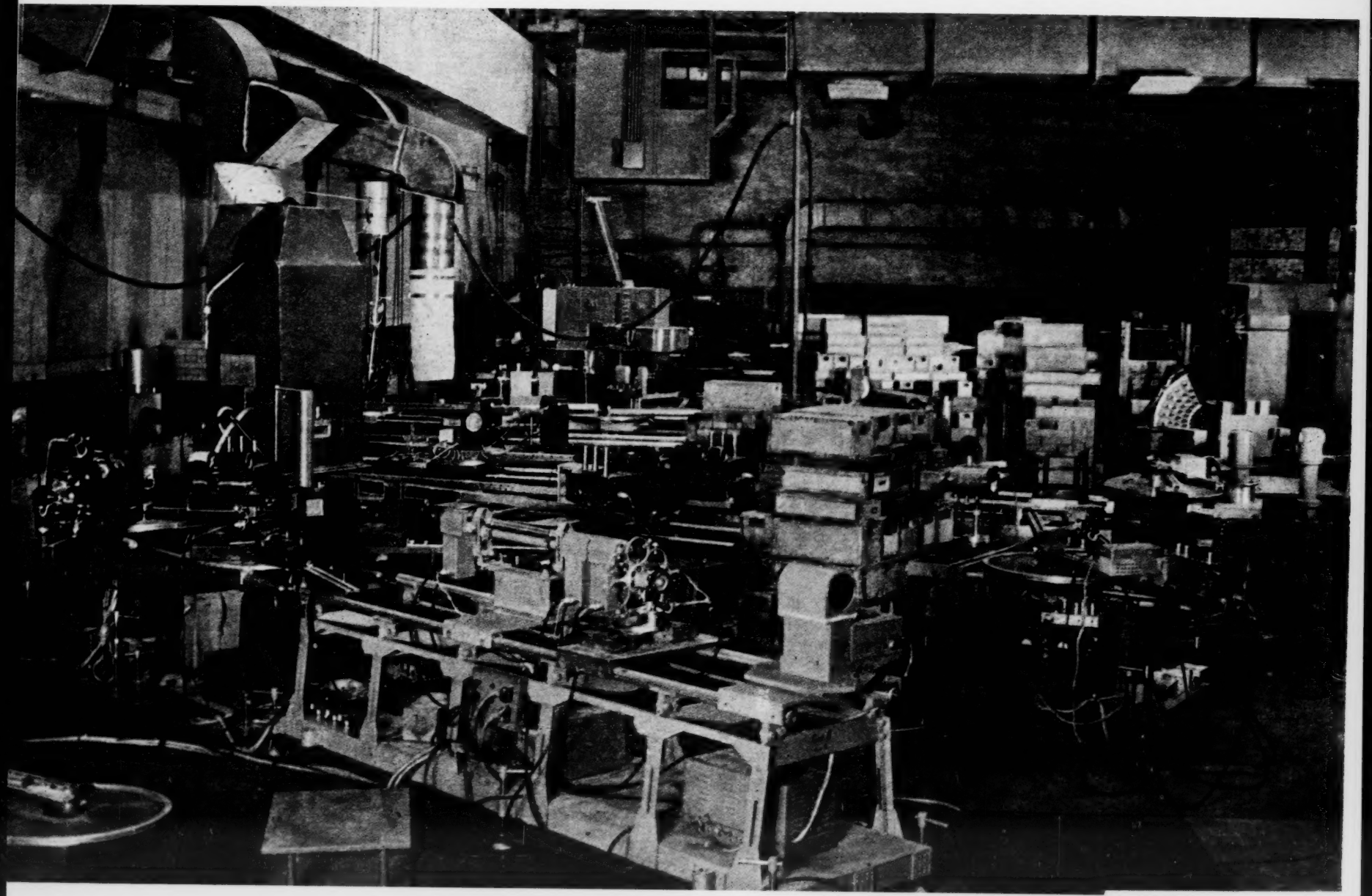

Fig. 30. Measuring pavillion.

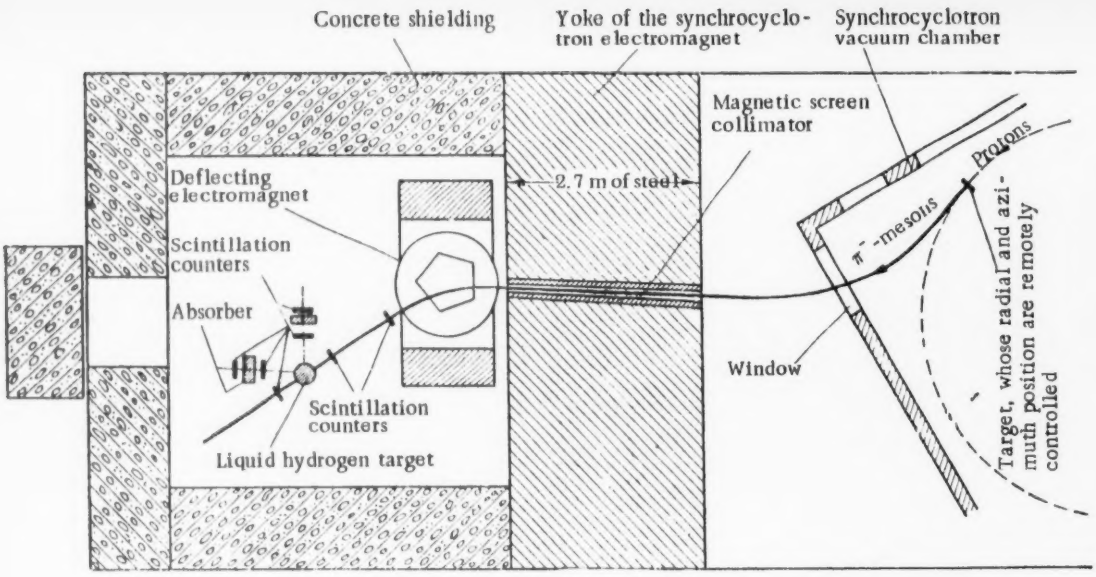

Fig. 31. Typical experimental setup for studying the scattering of high-energy charged π-mesons by protons.

The experimental apparatus used for studying particle scattering and meson production is often provided with special targets filled with liquid hydrogen or deuterium. Figure 37 gives an over-all view of one such target.

The fundamental part of the research involving the production of charged and neutral π-mesons in collisions of nucleons with nucleons or nuclei was performed with the aid of many-channel magnetic spectrometers in conjunction with gas-filled or scintillation counters (Figure 38). The electromagnets of these spectrometers have poles whose linear dimensions are about 1 m and give rise in their gaps (of about 10-15 cm) to a field of 15000-17000 oersteds. The magnets weigh about 35-50 tons. The electromagnet solenoids of the cloud chambers and diffusion chambers have about the same parameters as those given above.

A liquid hydrogen bubble chamber (Figure 39) was used in the experiments on production of charged π-mesons in neutron-proton collisions.

Individual interaction events between high-energy particles and nucleons or nuclei were also observed by means of photographic emulsions and emulsion chambers. The emulsions were scanned using microscopes provided with angle-measuring devices and large stages with very accurate travel. The marking of the emulsion chambers is performed in a special press with an illuminated grid designed and constructed in our laboratory.

In several experiments it is necessary to perform a preliminary focusing of the high-energy particle beam. This is done by electromagnetic quadrupole lenses, one of which is shown in Figure 40.

The difficult conditions under which the physical experiments were performed necessitated the design of a whole complex of special electronic equipment such as wide-band amplifiers, multiple-channel analyzers, etc. It was also necessary to develop stereoscopic photographic apparatus, reprojectors, and stereocomparators both for obtaining and observing photographs of the particle tracks in the cloud chambers, diffusion chambers, and bubble chambers. Figures 41 and 42 show some typical equipment designed in our laboratory.

A large amount of the nuclear research on the six-meter synchrocyclotron was performed by means of radiochemical analysis.*

*See the note on page 1273.

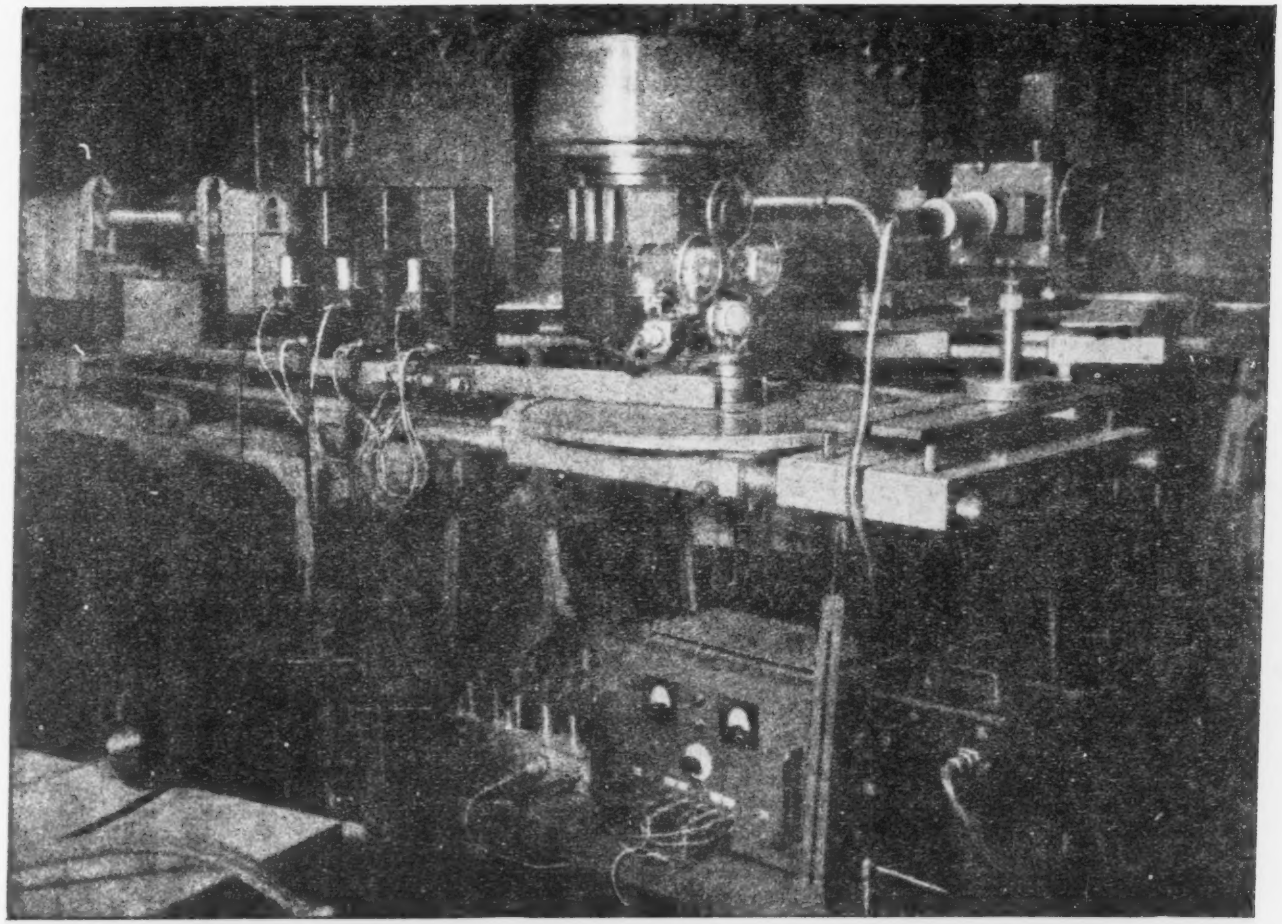

Fig. 32. Experimental apparatus for investigating the scattering of high-energy protons by protons and neutrons. A system of scintillation-counter telescopes records both secondary particles.

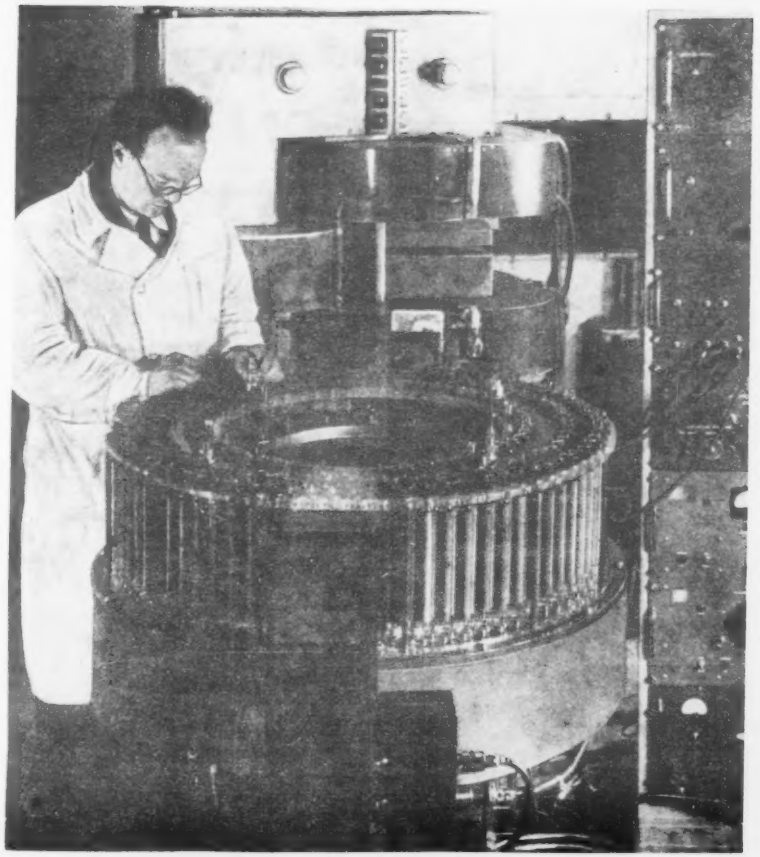

Fig. 33. A hodoscopic system of counters used in the study of high-energy π-meson scattering by hydrogen. The set of control counters subtends a solid angle of 2 steradians. The resolving time is $2 \cdot 10^{-6}$ sec. Pulse operation makes it possible to use ordinary gas-discharge counters for recording high-energy particles in the high background of radiation from the powerful accelerator.

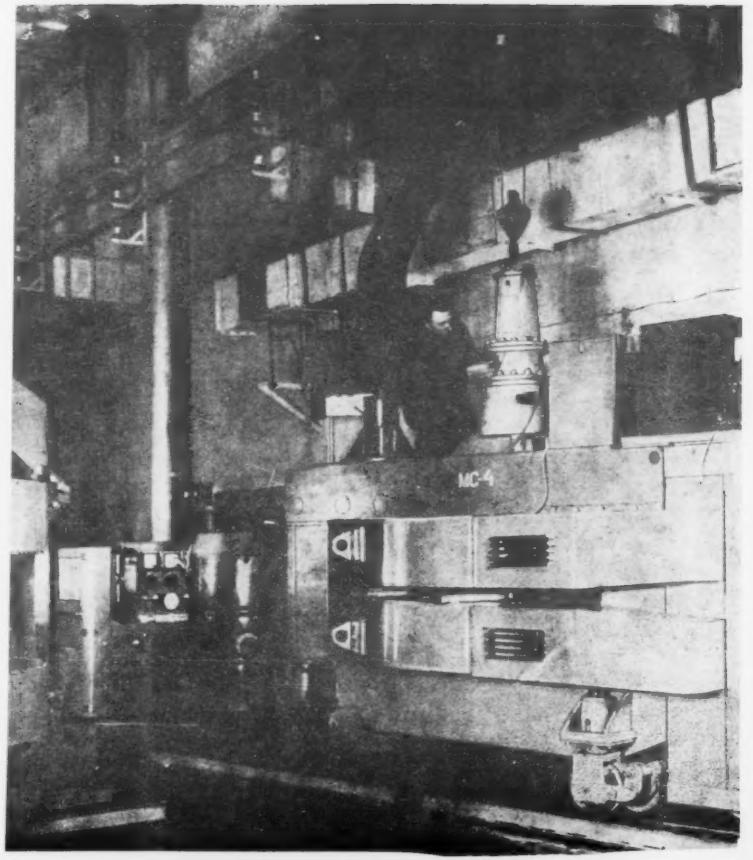

Fig. 34. High-pressure diffusion chamber in a magnetic field; this is used for studying the interaction of high-energy protons with protons and helium nuclei. The 300 mm diameter chamber is filled with hydrogen or helium to a pressure of 20 atmos. In its operating region the chamber is subjected to the pulsed magnetic field of 1600 oersteds. On the left is seen part of the yoke of the deflecting electromagnet.

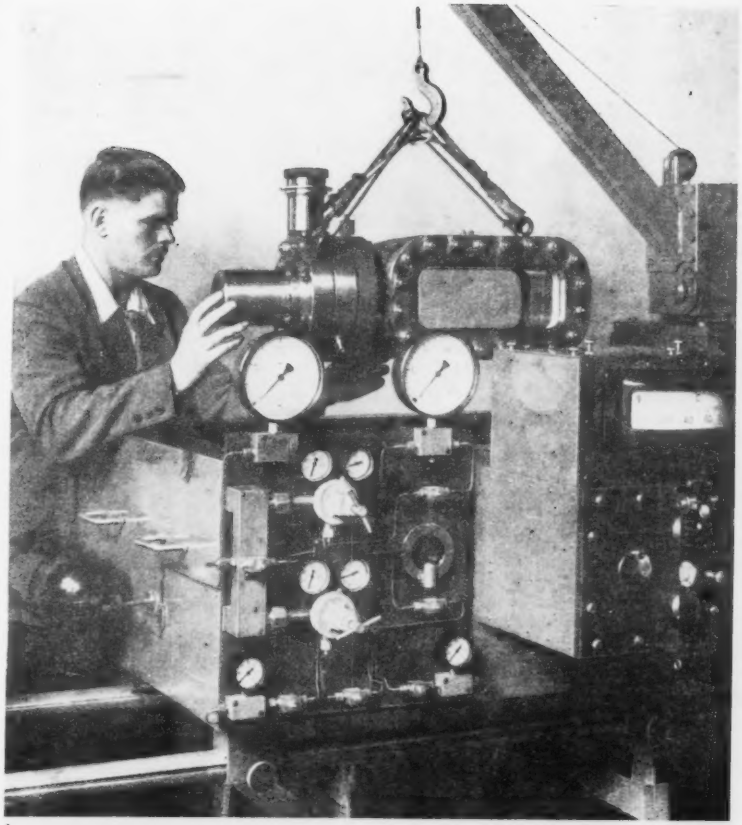

Fig. 35. The 4 liter propane bubble chamber. This is used for efficiently recording interaction processes and decay of elementary particles.

Fig. 36. The Wilson cloud chamber in a magnetic field, used for investigating the interaction of high-energy π-mesons with atomic nuclei. The chamber is 400 mm in diameter and 100 mm high. The pulsed magnetic field has a strength of 13500 oersteds. In the rear is seen the deflecting electromagnet.

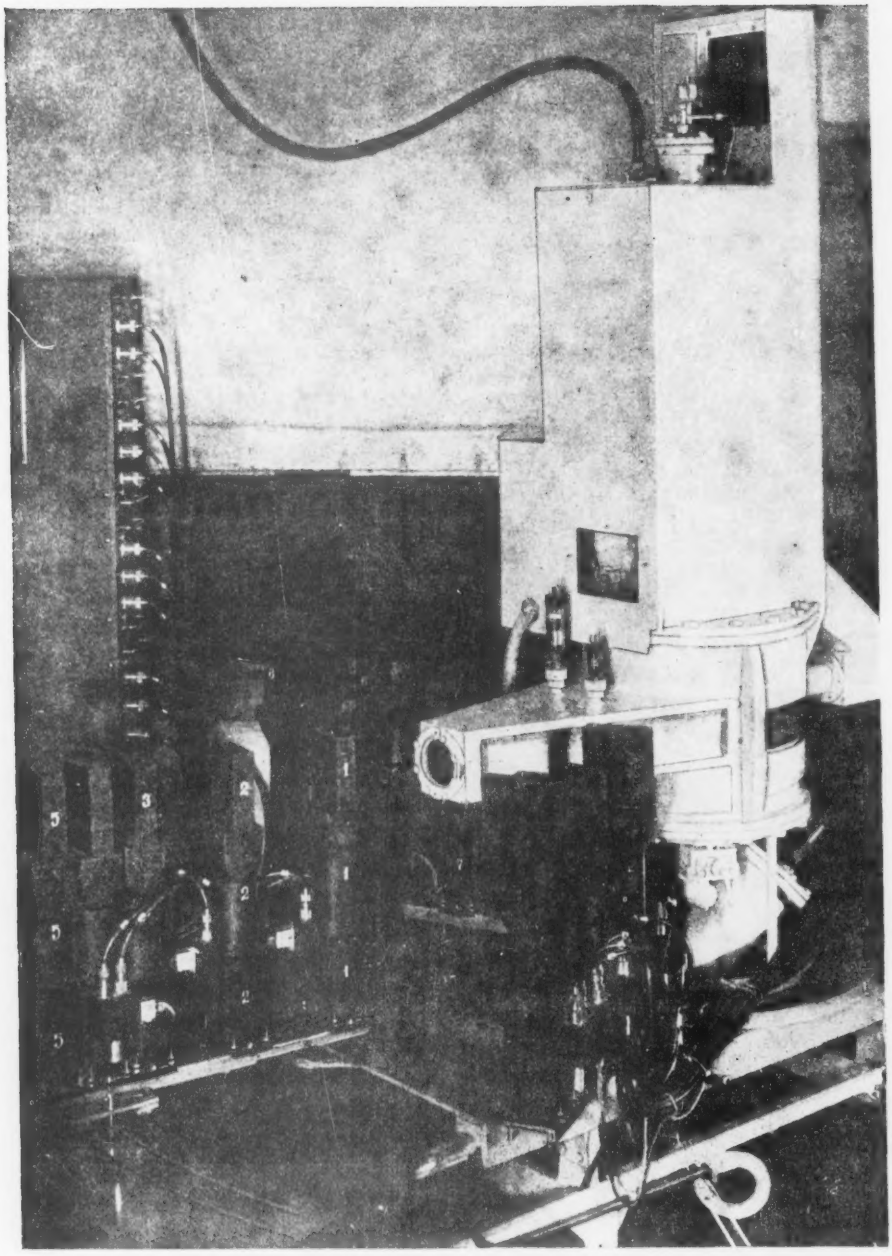

Fig. 37. Over-all view of the apparatus for investigating inelastic collisions of polarized protons with protons. The secondary particles are recorded by telescopes of large scintillation counters. The encased hydrogen-deuterium target (in the photograph) will maintain the liquid hydrogen in a 3.9 cm diameter operating cylinder for 50 hours. For background measurements the liquid hydrogen can be removed from the operating cylinder into a special container, and then pumped back without losses.

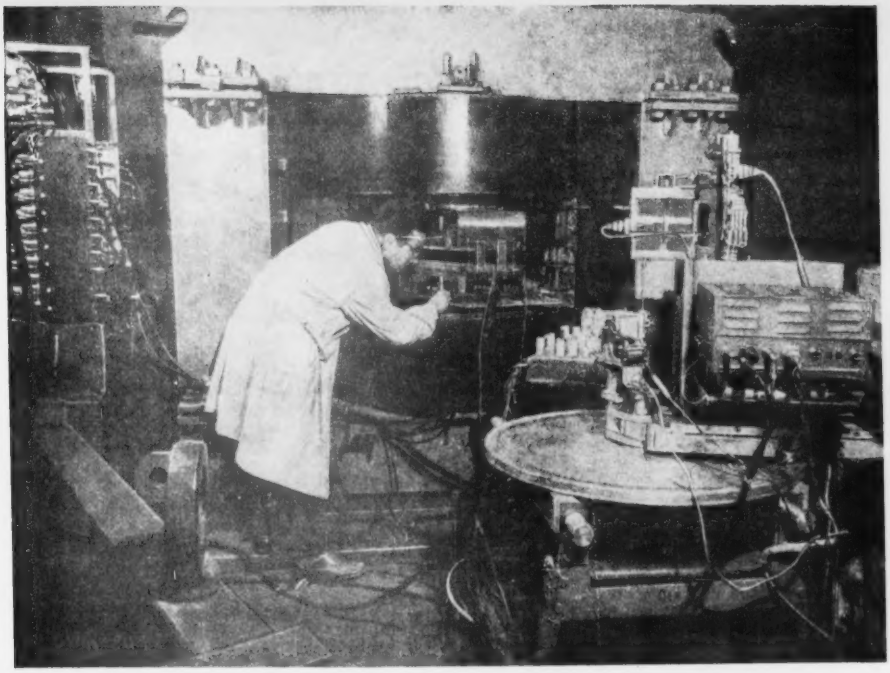

Fig. 38. Magnetic spectrometer used in experiments on the $n + p \rightarrow \pi^0 + d$ reaction. The apparatus records both products of the reaction simultaneously. The deuterons are detected by proportional counters, and their momentum is simultaneously analyzed in a magnetic field. The π^0-mesons are recorded by means of their decay, γ-rays with the aid of scintillation-counter telescopes.

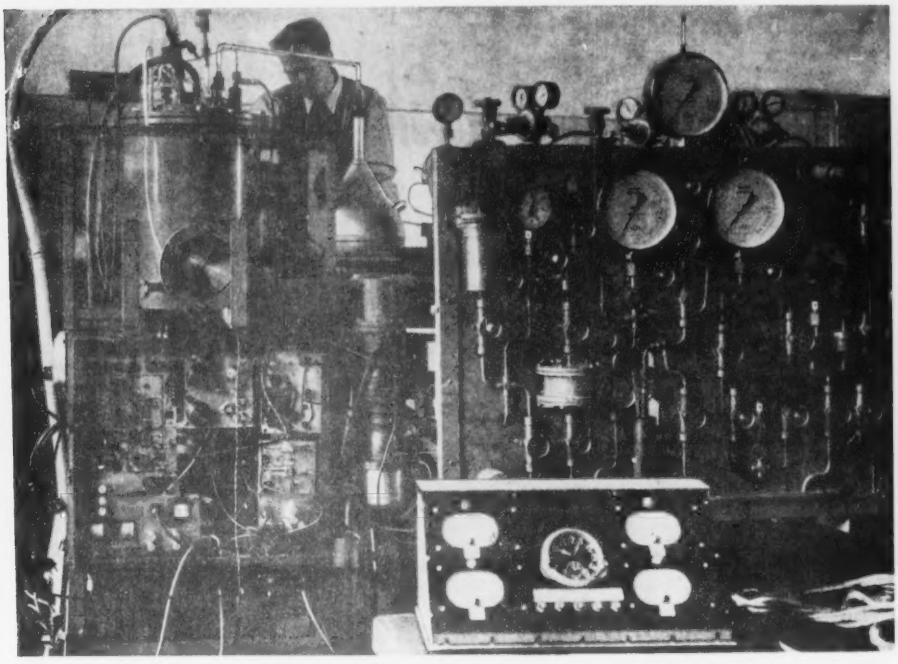

Fig. 39. The 1 liter liquid-hydrogen bubble chamber with its operating system (Heat Technology Laboratory, Academy of Sciences, USSR); it is used to study the interaction of high-energy particles with hydrogen.

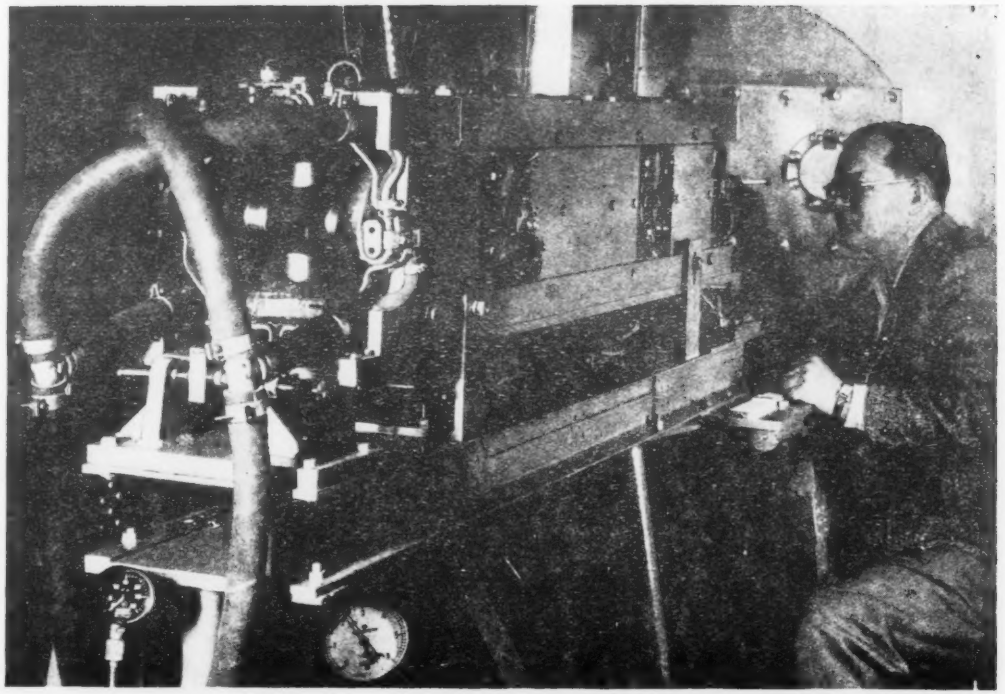

Fig. 40. Three-section magnetic lens for focusing a high-energy particle beam. The focal length of the lens for protons whose momentum is 1200 Mev/c is 2.5 m, the aperture is 80 mm, and the magnetic field gradient is 2000 oersteds/cm.

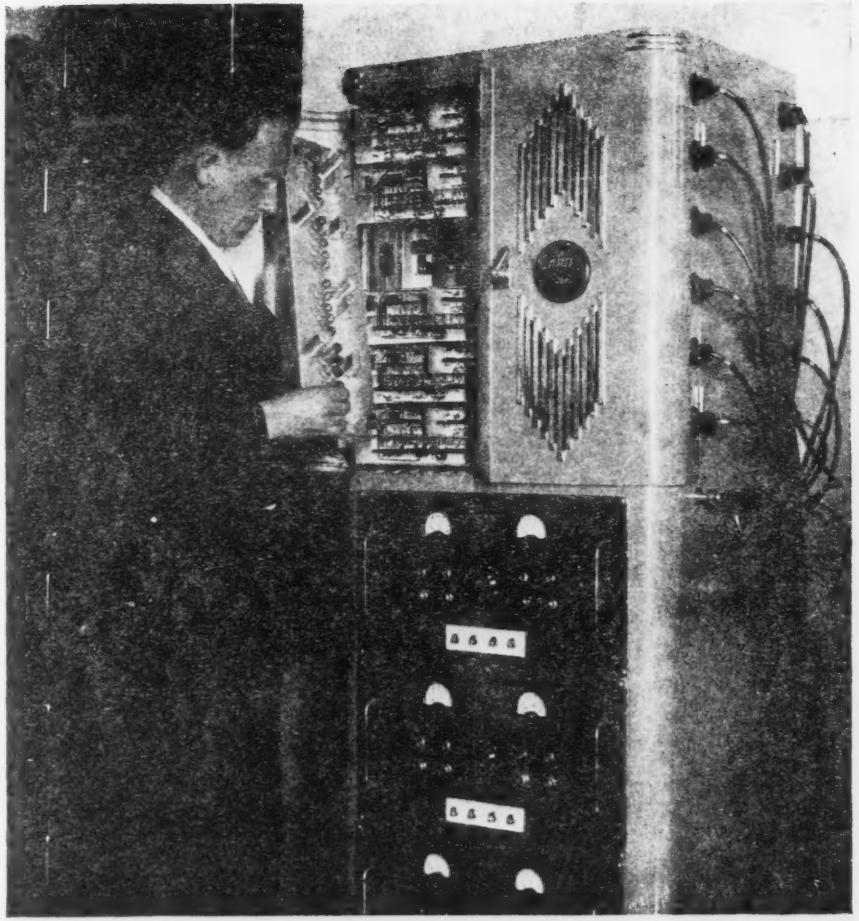

Fig. 41. A twelve-channel amplifier of scintillation counter pulses. Each channel provides 40 db amplification, and the upper passband frequency is 140 Mc.

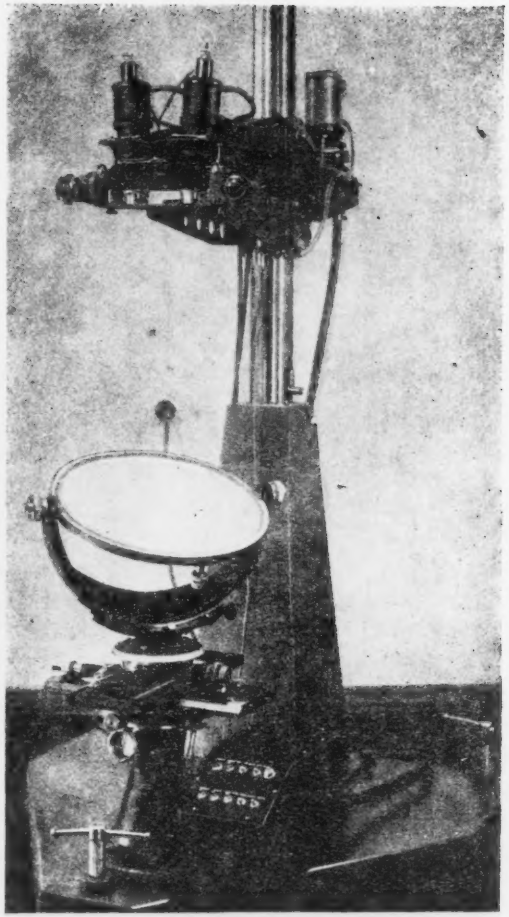

Fig. 42. A reprojector, an apparatus for determining the position in space of charged-particle tracks from stereoscopic photographs obtained in a cloud chamber, a diffusion chamber, or a bubble chamber. The screen diameter is 40 mm.

SUMMARY

In brief summation of the physics research performed on the six-meter synchrocyclotron in the Laboratory for Nuclear Problems, one may say that it has contributed valuable information to high-energy physics. It has broadened our knowledge in this field of modern physics and it has aided in exposing a series of new important problems and indicating effective methods for their study.

To a large extent it is due to this research that the young science of high-energy physics has come to occupy a lasting place among the other sciences of our nation.

Work on the six-meter synchrocyclotron has proved a good school in developing a large group of Soviet scientists with a mastery of modern physics, as well as engineers and designers with various specialties who have become familiar with totally new techniques.

During 1956-1957, as a result of the organization of the Joint Institute for Nuclear Research, the laboratories of the Institute have been enriched by scientists from foreign countries. The Institute has become an international center for nuclear research, and one of its goals is the instruction of groups of physicists from the twelve nations participating in the Institute.

On the glorious fortieth anniversary of the Great October, The High-Energy Laboratory of the Joint Institute for Nuclear Research has turned on the gigantic 10 Bev proton synchrotron, opening for modern nuclear physics additional new perspectives for further development.

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THE INTERACTION OF SLOW NEUTRONS WITH NUCLEI

(REVIEW)

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An intensive investigation of the interaction of neutrons with nuclei began in the USSR [1] and abroad [2] soon after the discovery of the neutron by Chadwick [3]. The neutron turned out to be a very useful particle for the investigation of the nuclear energy levels and for the production of new nuclear reactions since, due to the absence of the Coulomb barrier, even a very slow neutron easily penetrates the nucleus. The properties of the compound nucleus formed can be studied through the dependence of the reaction cross section on the neutron energy. However, because of the low intensity of the neutron sources existing in those days only measurements over a wide neutron-energy spectrum were possible.

After the construction of nuclear reactors it became possible to produce sufficiently intense beams of monochromatic neutrons.

For this purpose resonance detectors made from a material which interacts strongly with neutrons of only a single definite energy are used [4, 5]. This method enables the measurements of the interaction cross section in very limited energy intervals and, therefore, it cannot give full data on the energy-dependence of the cross sections.

In work with nuclear reactors the method of boron filters, developed as early as 1935-1936, is also used [6, 7]. The method of boron filters consists in selecting by means of plates of various thicknesses some relatively wide region of the spectrum. With this method reliable data can only be obtained for substances having one or two sufficiently far-removed resonance levels.

For a detailed study of the energy dependence of the effective cross section it is necessary to have monochromatic beams of neutrons. Such beams can be obtained by utilizing the diffraction of neutrons from a single crystal. The first reports of crystal neutron spectrometers appeared in 1946 [8]; somewhat later improved devices were constructed [9-14] which used bent crystals which considerably decreased the area of cross section of the reflected beams. This enabled the resolving power to be increased and to decrease the size of the detector. It became possible to use, in samples of small dimensions, small quantities of separated isotopes; the signal-to-noise ratio was improved.

The resolving power and, what is more important, the intensity of the reflected beam in a crystal spectrometer fall rapidly with increasing energy. As the energy is increased, the reflected beam approaches the incident beam and this greatly complicates the measurements. Therefore, crystal monochromators are used for accurate measurements up to an energy $\sim$10-20 ev.

Monoenergetic beams of slow neutrons can also be obtained by means of mechanical monochromators in which the separation of the neutrons according to energy is accomplished by sorting them with respect to their time of flight. Such an arrangement, first described by Dunning et al. [15], in principle is analogous to the apparatus for the measurement of the velocity of a bullet. Mechanical monochromators [16, 17] give narrow neutron spectra only in the energy region lower than a few electron volts, and they are in competition with crystal spectrometers right up to thermal energies.

Therefore, at the present time, mechanical monochromators in the energy range indicated are only used as auxiliary equipment, for example, for the absorption of high-order reflections [17]. In the region of cold neu-

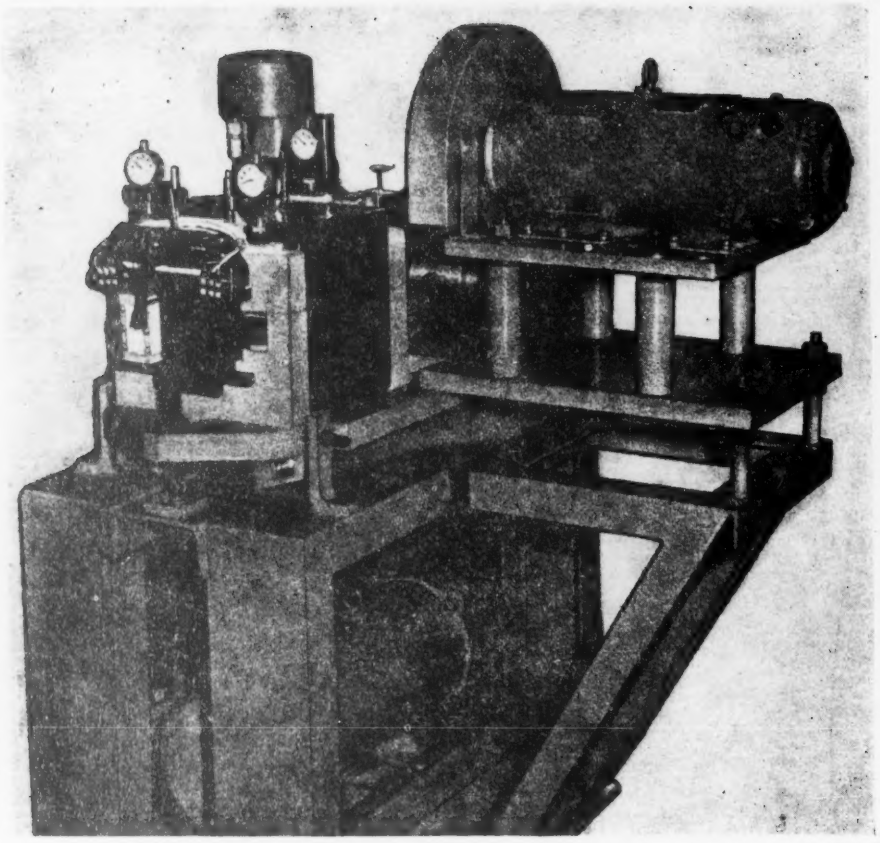


Fig. 1. A mechanical chopper for the production of short neutron pulses [23, 24]. Rotor – transverse, rotated with a speed of up to 25,000 rpm by a direct-current motor through a friction transmission.

trons mechanical monochromators are the most suitable type of equipment [16].

Sufficiently monochromatic neutrons with energies higher than several tens kev can be obtained from the reactions of accelerated charged particles with various light nuclei [18]. The energy of the neutrons produced in the reactions has a spread of several kev, which is caused by the energy loss of the charged particle in the target. By using thin targets the spread in the energy can be decreased. However, the intensity of the neutron beam greatly falls and the use of such a method becomes undesirable.

Another method of determining energy is based on the production of an interrupted neutron beam followed by the measurement of the time in which the particles traverse the distance between the source and the detector. The corresponding experimental arrangement, the so-called time-of-flight neutron spectrometer, consists of two parts: a pulsing neutron source and a radio-frequency device which sorts the registered neutrons according to their time-of-flight. A useful quantity determining the quality of a spectrometer is the resolving power expressed in units of $\Delta t/L$, where Δt is the uncertainty in the time-of-flight* and L is the flight distance.

One of the methods for obtaining an interrupted neutron beam is by modulating the source of accelerated charged particles. The neutrons emitted in the reactions of these particles with target nuclei are slowed down to

* Δt is the full width at half height of the resolution function and depends on the neutron pulse duration, the channel width, the counter-discharge time, etc.

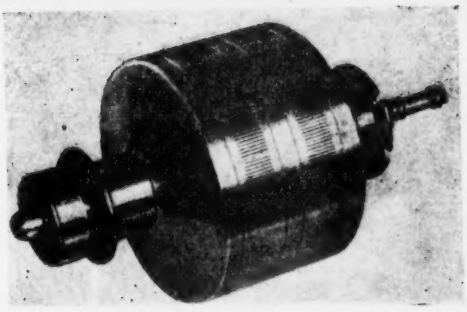


Fig. 2. The rotor of the mechanical chopper shown in Figure 1. The rotor has two systems of slits: straight slits for transmitting high-energy neutrons, and bent – for low energies.

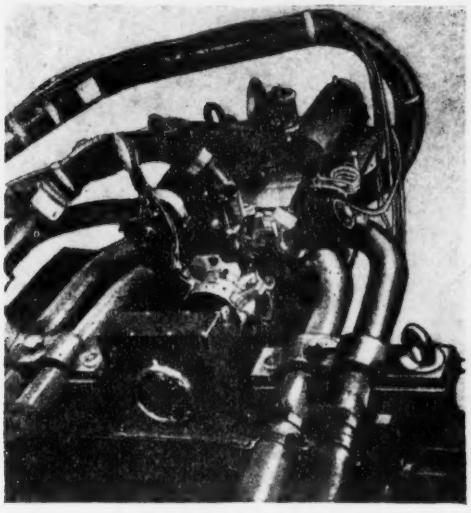


Fig. 3. A mechanical chopper with a longitudinal rotor [25]. The rotor is rotated by an air turbine with a speed of up to 25,000 rpm.

the required energy by passing them through a moderator. The modulation of the cyclotron ion beam, although comparatively simple, does not enable the production of very short pulses and, consequently, good resolution cannot be obtained. Therefore, in recent years attempts are being made to decrease the pulse duration at the expense of the deflection of the accelerated beam. The duration of the neutron pulses obtained in this way can be less than 10^{-8} sec [19, 20].

The pulse modulation of nonmonochromatic neutrons can be achieved by a mechanical method. In 1936-1937 at the Leningrad University Nemilov[21] built a mechanical selector of the Dunning type [15], in which instead of the second disc an ionization chamber with a modulated sensitivity was used. Nemilov's apparatus must be considered as the first mechanical neutron selector; however, no measurements made with this apparatus were published. Mechanical neutron selectors received widespread use only after the appearance of powerful neutron sources – nuclear reactors. In 1947 a mechanical chopper for thermal neutrons which is in the form of a high-speed rotating drum, consisting of parallel alternating strips of cadmium and aluminum, was installed in the Fermi Laboratory at Argonne. In measurements with resonance neutrons, for which cadmium becomes too transparent, the rotor was made from steel, nickel, plastics, i.e., materials having a high scattering cross section. Thus, in 1950, in the AN SSSR Thermotechnical Laboratory [23, 24] and in the AN SSSR Institute of Atomic Energy [25] Fermi-type choppers were constructed, which were made from nickel-chromium alloy and nickel covered by a thin layer of cadmium, respectively. In 1951, at the Argonne Laboratory a steel chopper with a longitudinal rotor was constructed, whose axis of rotation, as well as the slits, was parallel to the neutron-beam axis [26]. At the Brookhaven Laboratory a mechanical chopper, having a transverse rotor 76 cm in diameter and 8 pairs of slits, has been in operation since 1953. The rotor is made from plastic, placed in a duralumin frame; in the latest model of the chopper [28] to decrease the γ-ray background a steel core 7.6 cm in diameter has been placed at the center of the rotor. The resolving time of neutron spectrometers with mechanical choppers which are in operation at the present time, is 0.05-0.1 μsec/m (see Table 1).

A big advantage of mechanical choppers (particularly single-slit ones) by comparison with nonmechanical spectrometers is the possibility of using small samples (~ 5 mm^2 in area) which is important with measurements on separated isotopes.

The sorting of neutrons by their time-of-flight is made with the help of electronic equipment – time-of-flight analyzers. The simplest device of this type is an oscillograph, whose time base is triggered by the starting pulse while the signal to be analyzed is put on the deflecting plates [29, 30]. To obtain the necessary accuracy for spectrum measurements it is necessary to divide the region investigated during each determination into several hundred small intervals or "channels" and to collect up to 10^4 pulses in each. The processing of data obtained with an oscillograph becomes hard to carry out in practice. Therefore, multi-channel analyzers were designed in which the sorting according to the time-of-flight and the addition of the number of counts in each channel is

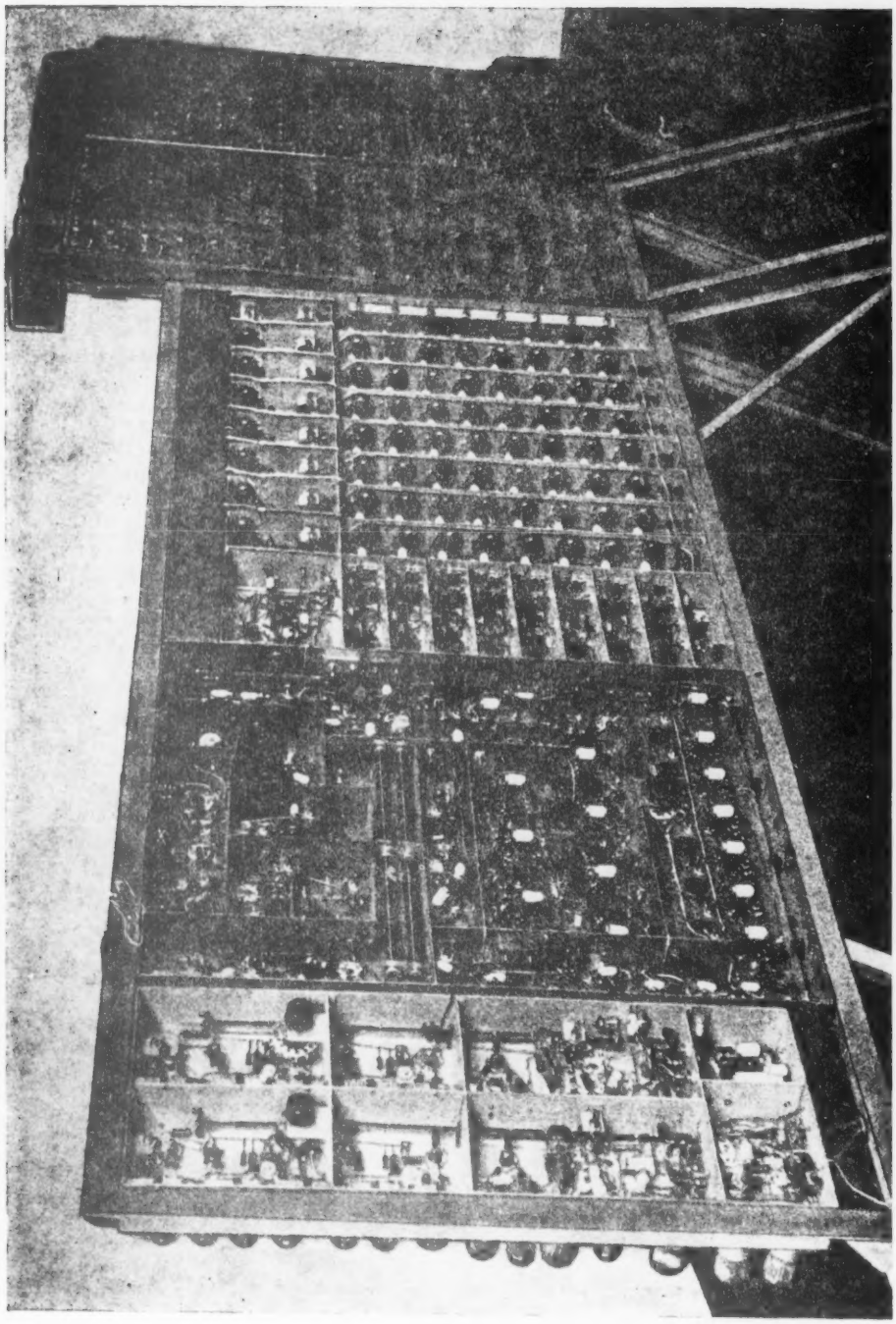


Fig. 4. Matrix-type analyzer for a mechanical selector [24].

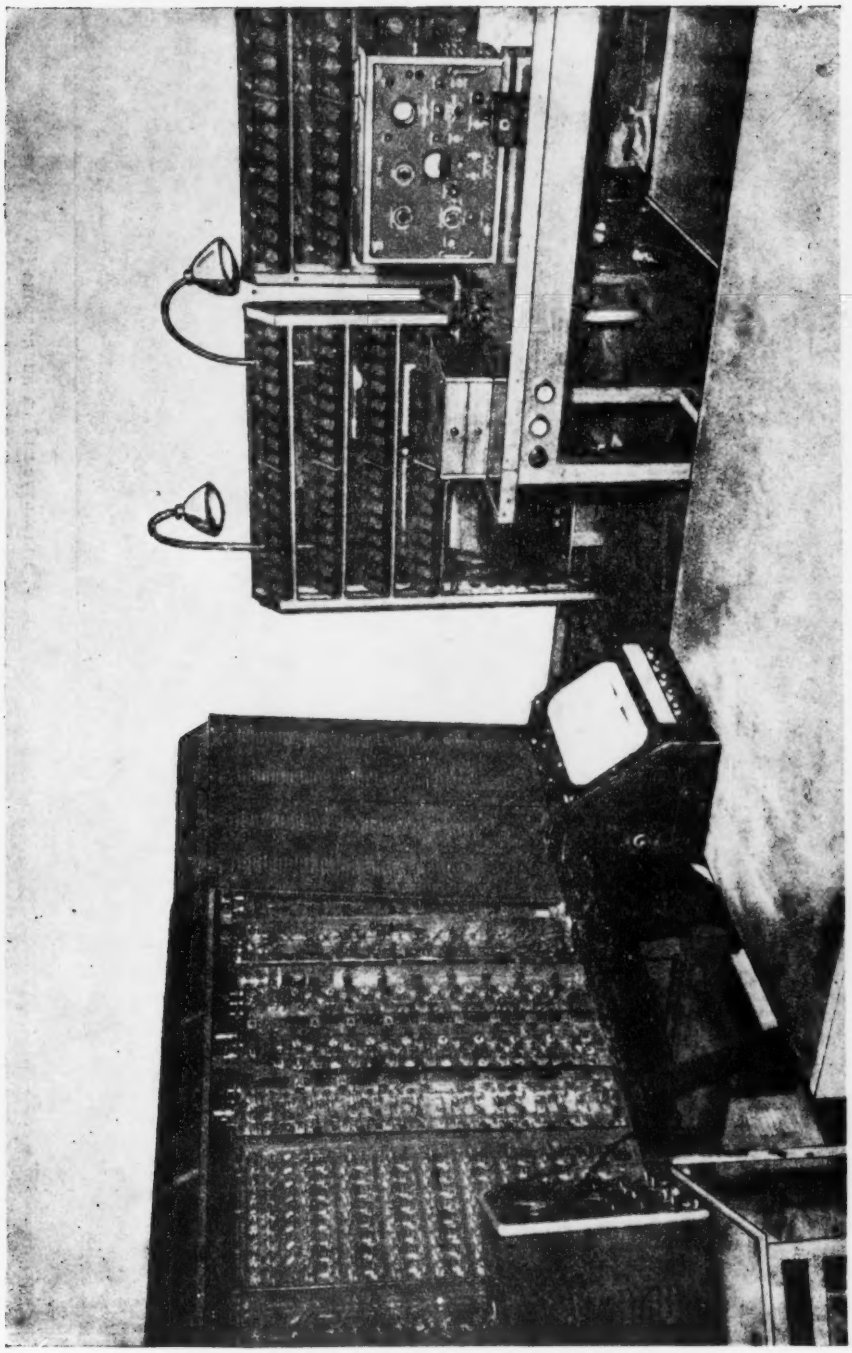


Fig. 5a. A 256-channel matrix analyzer used with a cyclotron.

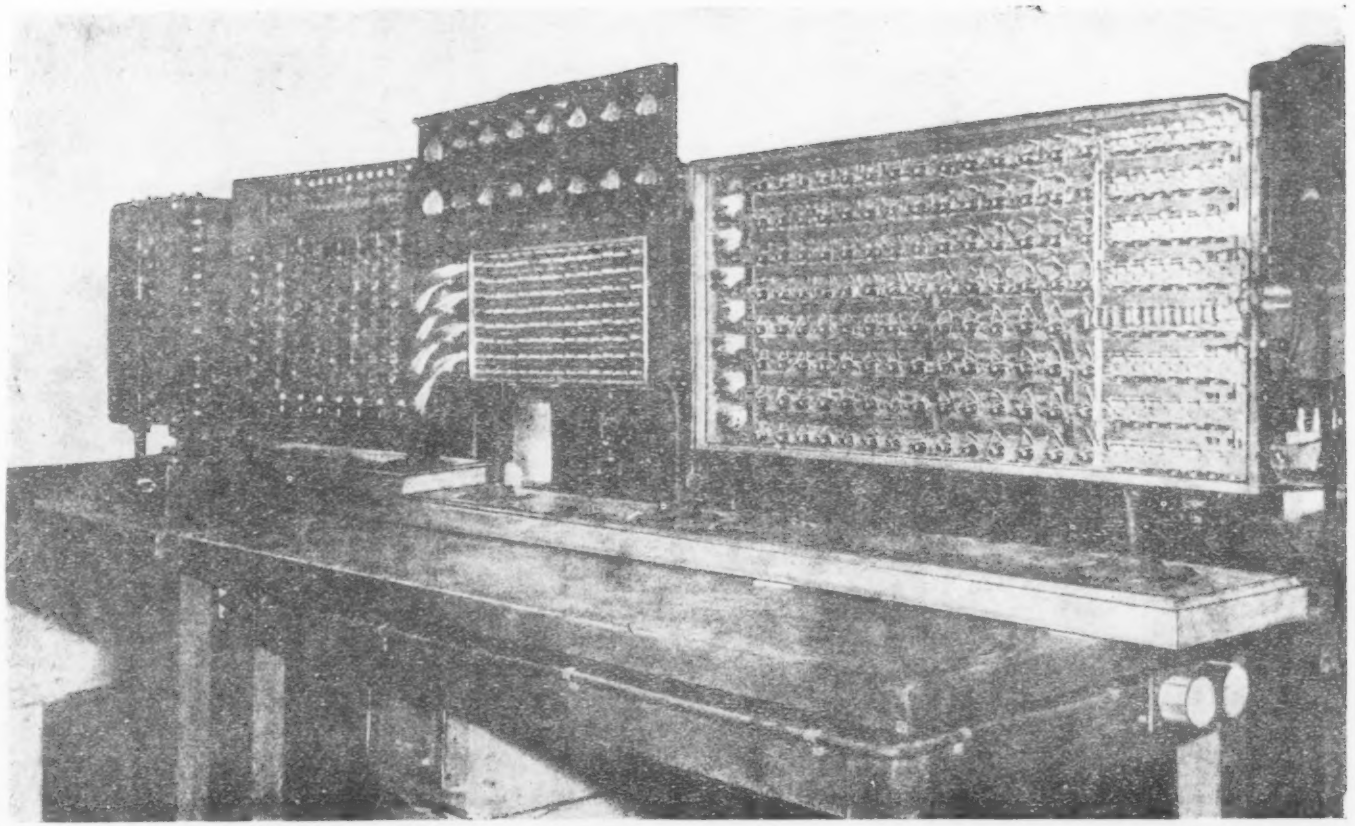
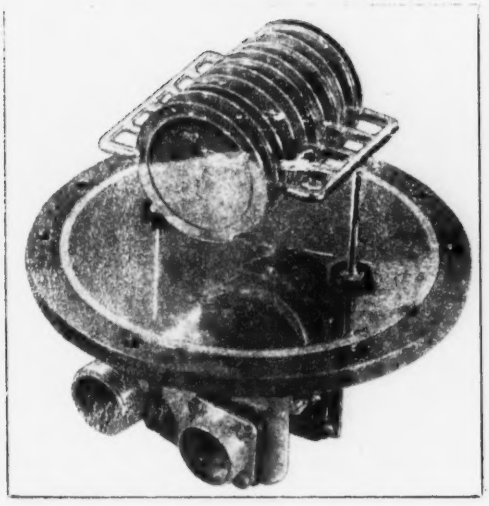


Fig. 5b. A compact 100-channel analyzer used with a cyclotron [37].



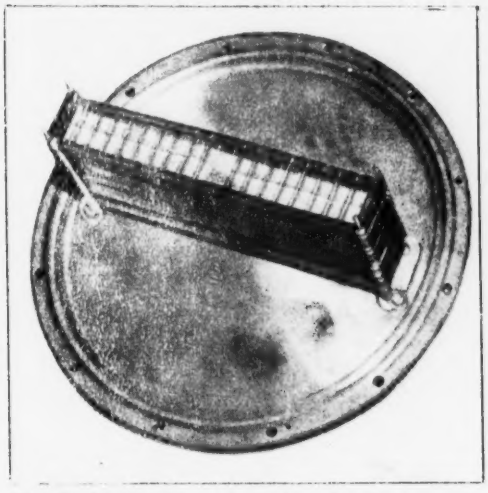


Fig. 6. Multi-electrode fission chambers containing large quantities of fissile isotopes. Above – chamber with 22 mg of Pu^{239} [25]; below – chamber containing 280 mg of U^{233} [105].

carried out automatically during the registration of the neutrons. The first such device was proposed and constructed by Nemilov [21]. Somewhat later, in 1938, an analogous device was described by Alvarez [31]. Improved analyzers were described in References [25, 31-35].

At the present time a somewhat modified system is frequently used in which not only the starting pulse, but also the pulse from the neutron detector, is stored [24, 36]. This improvement enabled the number of storage locations to be decreased by $\sqrt{N}/2$ times (N is the number of analyzer channels). Since the storage devices used consist of a series of switching units connected in a definite manner, the use of two stored coincidences appreciably decreased the number of radio valves in each analyzer channel. Such equipment can be divided into two types: fast analyzers which can count several pulses in one cycle [24, 37-41] and analyzers for slow counting which only operate once per cycle [27, 40].

To obtain the necessary time scale it is sometimes convenient to use, instead of a commutator, a single counting circuit, employing in some way all of its possible states [24]. Beliaevskii [42], using this principle, constructed a 16-channel analyzer in which the various states are set up with the help of numerous coincidence circuits.

Systems with two stored coincidences and an output to mechanical counters become very unwieldy when the number of channels is several hundred. The appearance of new types of memory devices and the extensive development of computers enabled the creation of new types of analyzers using these achievements [25, 40, 44-49].

A group of workers [50] designed a spectrometer in which, for the determination of neutron energies, the slowing-down time in a substance of high atomic weight is measured. A device of this nature, with a very limited energy resolution has a very high luminosity and this makes possible its use with comparatively simple neutron sources, as well as its use for the measurement of capture cross sections.

In conclusion of the very brief review of neutron spectrometers, the table gives the more important characteristics of the majority of the neutron spectrometers known at the present time (see Table 1).

Measurements with neutron spectrometers enable the determination of some characteristics of nuclei. Such characteristics are: scattering cross sections, the neutron, radiation and fission widths, and the separation between nuclear energy levels. The characteristics indicated refer to nuclear levels in a comparatively small energy interval (~ 20-1000 ev), lying 5-7 Mev (binding energy of the neutron in the target nucleus) above the ground state. At the present time, the neutron widths of levels are measured with the highest accuracy, since with a suitable choice of sample thickness they are determined as the result of only one measurement, for example, the area above the curve giving the resonance transmission of the sample.

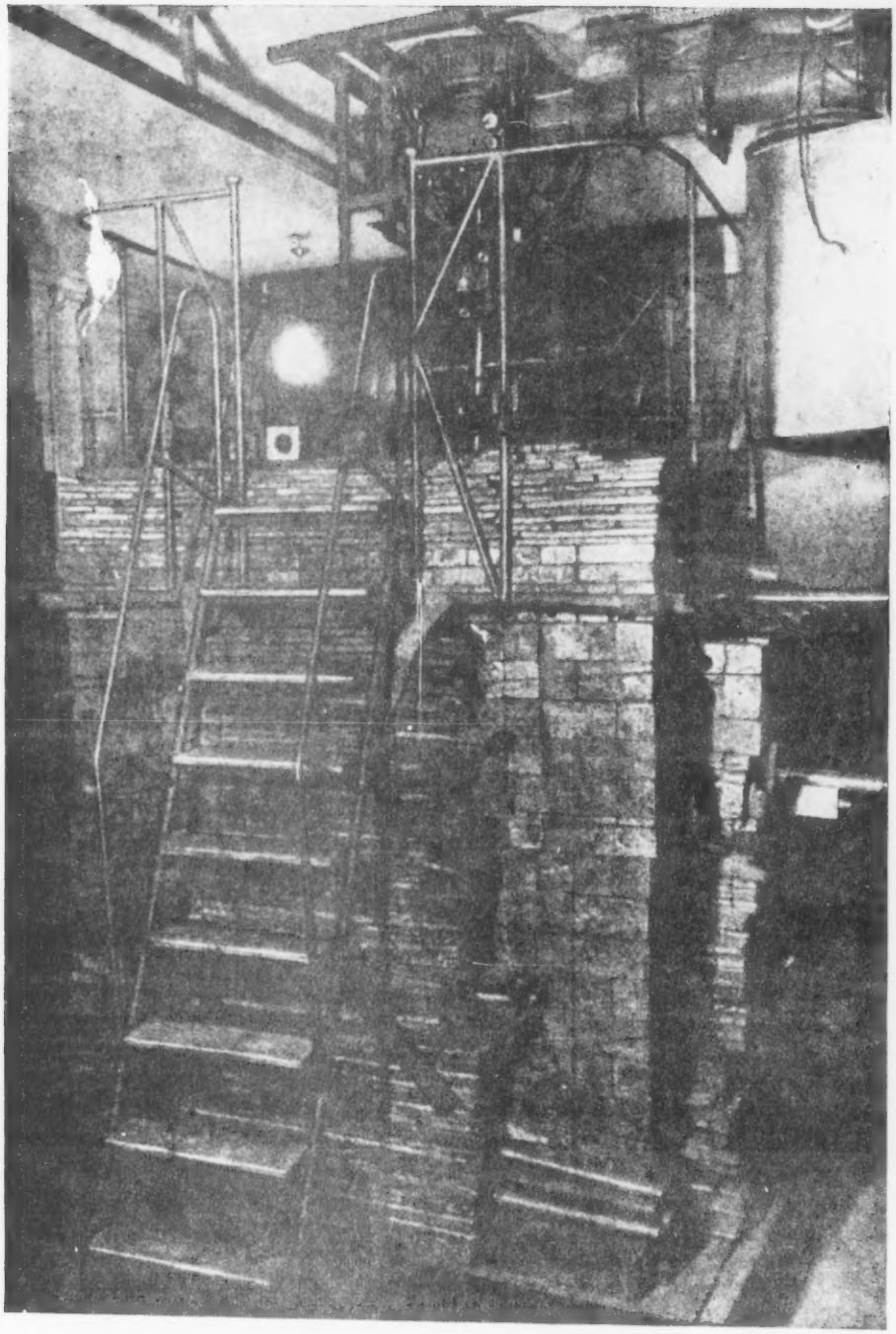


Fig. 7. Lead cube of the time-of-flight neutron spectrometer [50]. The size of the cube is $2 \times 2 \times 2.3$ m^3. The neutron source is a zirconium-tritium target irradiated by deuterons which are accelerated in a linear accelerator. Part of the target with an electric shutter can be seen at the top. At the right, in the center of the cube, the neutron detector can be seen placed into the measurement channel.

TABLE 1

Neutron Spectrometers

Location of equipment	Δt, μsec	L, in m	Δt/L, μsec/m	Remarks	References
Crystal spectrometers					
Thermotechnical laboratory (USSR)			1	Bent quartz crystal with $(13\bar{4}0)$ and $(10\bar{1}0)$ planes	[10]
Brookhaven Laboratory (USA)			0.127	Beryllium crystal with $(22\bar{4}2)$ plane	[11]
			0.171	The same $(12\bar{3}1)$	
Argonne Laboratory (USA)			10	Lithium fluoride crystal with (100) plane	[12]
Oak Ridge Laboratory (USA)			4.5	Bent quartz crystal with (100) plane	[13]
MTR reactor (USA)			0.9	Sodium chloride crystal with (240) plane	[14]
Mechanical monochromators*					
Brookhaven Laboratory (USA)				Efficiency 80%. Intended for operation with a crystal spectrometer	[17]
Los Alamos Laboratory (USA)				Efficiency 60%. $\Delta E/E = 30\%$ at $\lambda = 1$ A	[16]
Neutron selectors used with accelerators					
Thermotechnical Laboratory (USSR)	2	16	0.12	Cyclotron	[37]
Brookhaven Laboratory (USA)	0.7-2	4.3	0.2	Cyclotron	[51]
Yale University (USA)	0.2-4	5-15	0.4	Electron accelerator	[51, 52]
Harwell Laboratory (England)	2	10	0.2	Electron accelerator	[53]
General Electric Laboratory (USA)	0.4-1.4	7-20	0.02	Betatron	[51, 54]
Columbia University (USA)	1	6	0.33	Cyclotron	[55]
Columbia University (USA)	0.5	35	0.014	Synchrocyclotron. Beam deflection perpendicular to the plane of the orbit	[19, 20]
Sweden	6	6	1	Cyclotron	[56]
Mechanical choppers					
Institute of Atomic Energy (USSR)	5	6.3	0.8	Transverse rotor	[25]
Institute of Atomic Energy (USSR)	3.2	26.5	0.12	Transverse rotor	[25]
Thermotechnical Laboratory (USSR)	1.3	19	0.07	Transverse rotor	[23]
Brookhaven Laboratory (USA)	1	20	0.07	Transverse rotor	[27, 28]
Argonne Laboratory (USA)	4	40	0.1	Transverse rotor	[26, 57]
Argonne Laboratory (USA)	2	60	0.04	Transverse rotor	[58]
MTR reactor (USA)	1.6	45	0.05	Transverse rotor	[59]
Harwell Laboratory (England)	0.1	100	0.001	As yet not in operation. The beam is interrupted in two stages by three synchronous rotors.	[60]

*The description of several monochromators which apparently were not used for measurements can be found in Reference [4].

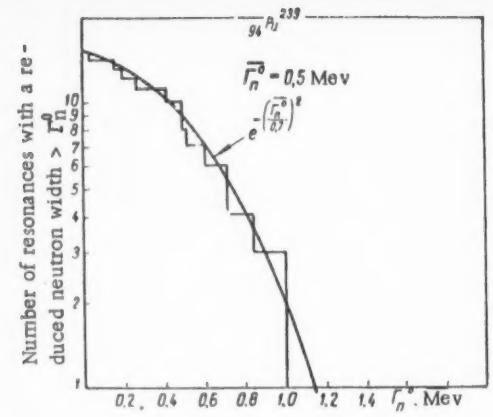

$_{94}Pu^{239}$
$\overline{\Gamma_n^0}$ = 0,5 Mev
$e^{-\left(\frac{\Gamma_n^0}{0.7}\right)^2}$
Number of resonances with a reduced neutron width > Γ_n^0
0.2 0.4 0.6 0.8 1.0 1.2 1.4 Γ_n^0, Mev

Fig. 8. The integral distribution of reduced neutron widths for Pu^{239} [64].

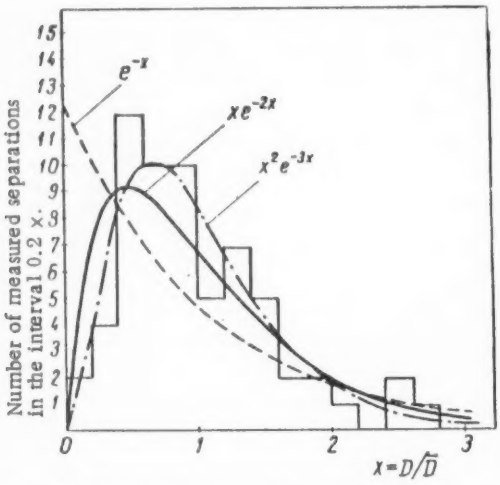


Fig. 10. The distribution of the separation between levels [66]. The experimental data are presented as a histogram.

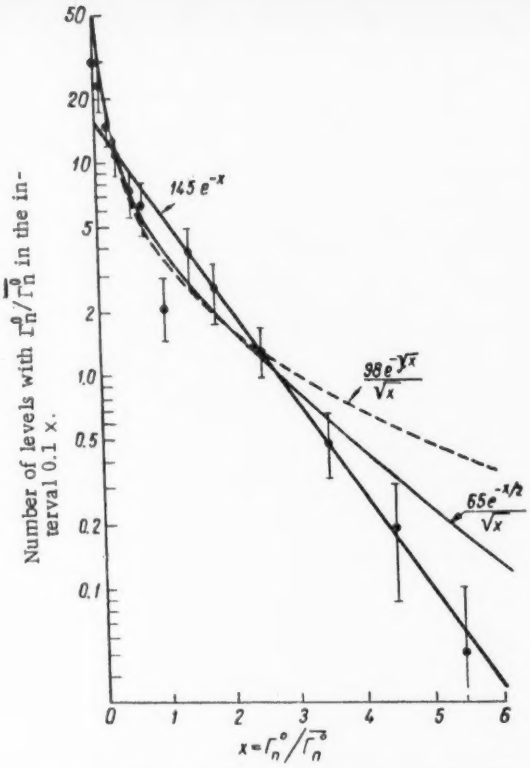


Fig. 9. The distribution of the values of the reduced neutron widths Γ_n^0, referred to the mean value $\overline{\Gamma_n^0}$ for each nucleus [65].

The distribution of reduced neutron widths $\Gamma_n^0 = \Gamma_n/\sqrt{E_0}$ can give useful information on the behavior of the wave function at the surface of the nucleus. From the experimental data it follows that the neutron widths, in contrast to the radiation widths, change very much from level to level. The analysis of the distribution of neutron widths for nonfissile elements [61] has shown that the distribution is adequately described by an exponential function of the form $\exp(-x)$, where $x = \Gamma_n^0/\overline{\Gamma_n^0}$. Bethe [62] has proposed another distribution, of the form $[\exp(-\sqrt{x})]/\sqrt{x}$, which describes better the experimentally-observed large number of very weak levels, as well as the considerable number of levels whose neutron widths are several times bigger than mean value $\overline{\Gamma_n^0}$. The laws indicated are purely empirical and have no theoretical basis. The neutron-width distribution law $[\exp(-x/2)]/\sqrt{x}$ [63] also agrees with the experimental data, but in contrast to the first two has some theoretical basis, namely, it corresponds to the Gaussian distribution for the amplitudes of the reduced neutron widths $\sqrt{\Gamma_n^0}$. Figures 8 and 9 show examples of various distributions taken from References [64] and [65].

In References [65] and [66], it is shown that the distribution of experimentally-measured separations between levels D does not agree with a random distribution of the form

$$w(E) \sim [\exp(-D/\overline{D})]/\overline{D}.$$

The observed number of closely-lying levels is much less than that expected from a random distribution. The authors explain this fact by the presence of "repulsion" between levels of the same spin system. An analysis of

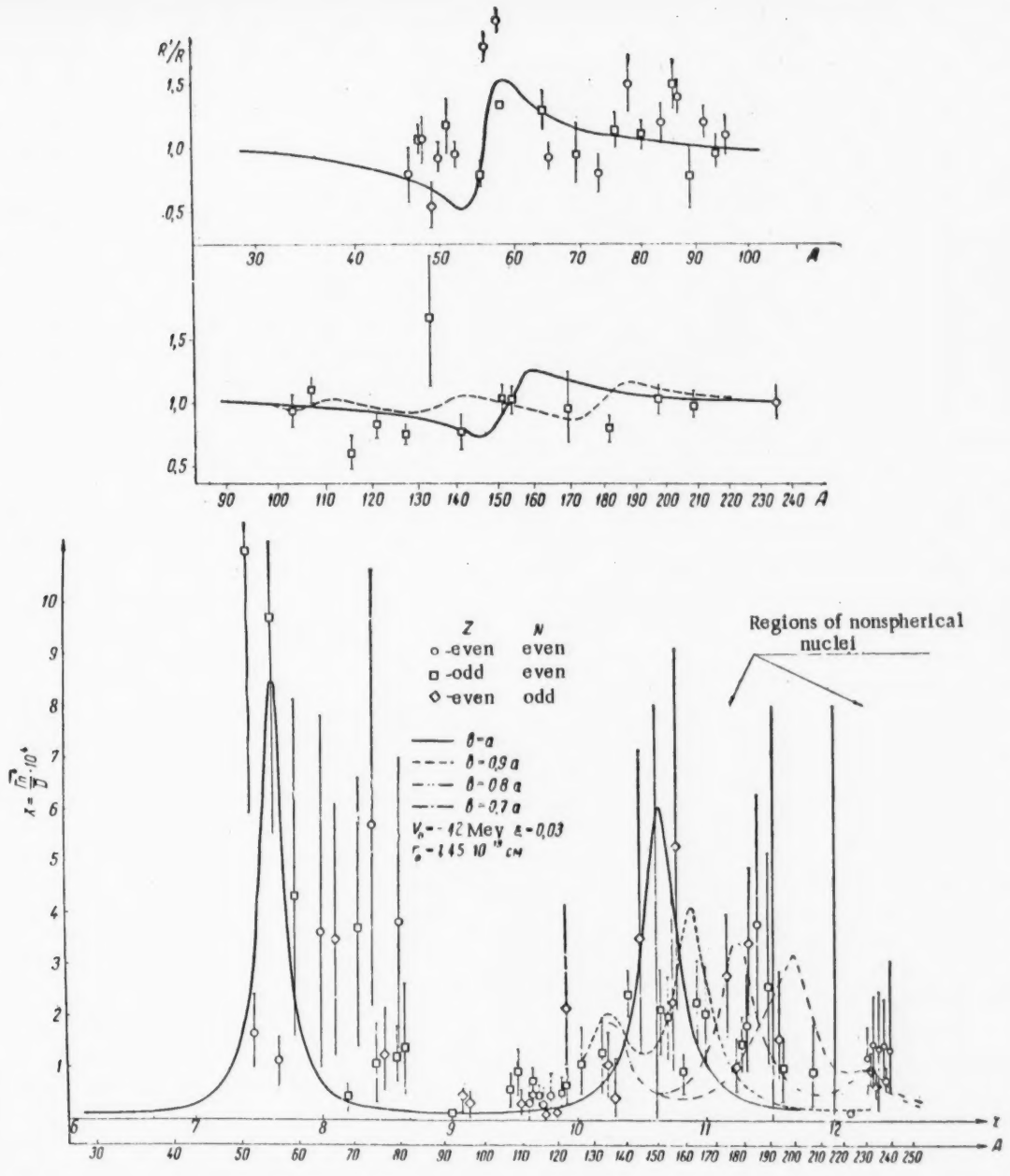


Fig. 11. Comparison of the experimental values of $\overline{\Gamma}_n^0/\overline{D}$ and the cross section for potential scattering σ_p with the semi-transparent nucleus model. The parameters for the model are shown in the figure. The nucleus is represented by an ellipsoid of revolution with semi-axes a and b. Z – number of protons; N – number of neutrons in the nucleus. Below – the dependence of $\overline{\Gamma}_n^0/\overline{D}$ on the atomic weight A. In the region A ~ 150-190 and A > 220 the theoretical curves are drawn for nuclei with various degrees of elongation $x = 2.03\ A^{1/3}$. Above – the ratio of the "effective radius" $R' = \sqrt{\frac{\sigma_p}{4\pi}}$ to the actual radius of the nucleus $R = r_0 A^{1/3}$ as a function of the atomic weight.

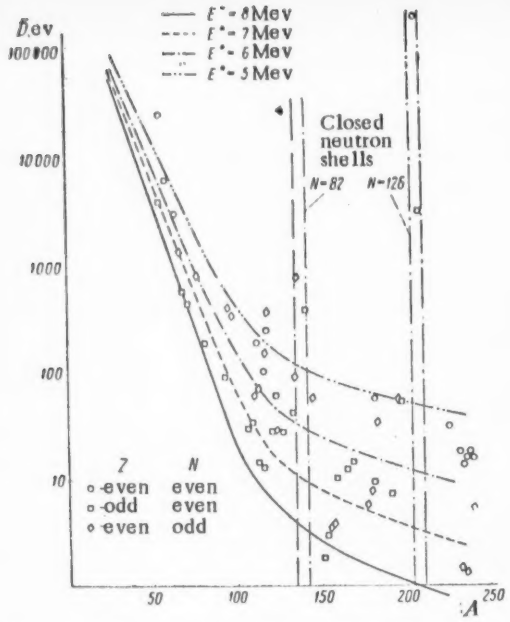


Fig. 12. The mean distance between levels $\overline{D}$ as a function of the atomic weight. The theoretical curves are drawn for various values of the excitation energy E^* of the compound nucleus.

this phenomenon has been made in this work for the case of two systems of noninteracting levels with approximately equal density. The best agreement with experimental data was obtained with a distribution of the form (Figure 10):

$$w(E) \sim (D/\overline{D})^2 \exp[-3(D/\overline{D})].$$

A more detailed comparison of the results is hindered by insufficient experimental data.

The ratio of the mean value of the reduced neutron width, $\overline{\Gamma_n^0}$, to the mean value of the separation between levels, $\overline{D}$, determines the penetrability of the nucleus surface for neutrons, or, more accurately, the probability for the formation of a compound nucleus. According to the "black nucleus" model (strong-binding model) this ratio is constant for all nuclei [67-69]. In the semi-transparent nucleus model [70] (in the literature – weak-binding model, single-particle model, optical model) the ratio $\overline{\Gamma_n^0}/D$ is a function of the atomic weight A (size of the nucleus) with very prominent maxima for $kR \sim (2n-1)\pi$, where k is the wave vector of the neutron inside the nucleus and $R = 1.45 \cdot 10^{-13} A^{1/3}$ is the radius of the nucleus in centimeters.

In References [71, 72] a comparison was made of the experimental values of $\overline{\Gamma_n^0}/\overline{D}$ with the values calculated on the basis of the theory of Feshbach, Porter and Weisskopf and a qualitative agreement between theory and experiment was pointed out, namely, maxima were observed for $A \simeq 50$ and $A \simeq 150$. A more detailed comparison of the results is not possible, mainly for two reasons. On the one hand, the experimental data are as yet not sufficiently complete or accurate; this is due to the fact that for each nucleus only a comparatively small number of levels have been measured (especially for elements with $A \simeq 50$-100). In addition, the values of Γ_n^0 and D, the separation between levels, show considerable fluctuations (by a factor of 10-100). Therefore, for a small number of levels the mean value has only a very limited significance. On the other hand, the theory itself is based on too general and simplified assumptions and does not take into account many details of nuclear structure, such as nonspherical shape, diffuseness of the nuclear boundary, irregular increase in size with increasing A (even-even and odd-even nuclei), etc.

In Reference [73] it was shown that taking into account the diffuseness of the nuclear boundary for neutrons with an energy of the order of several Mev leads to a big decrease and a smearing out of the maxima of $\overline{\Gamma_n^0}/\overline{D}$ as a function of A. In Reference [74], on the basis of the semi-transparent nucleus model, the dependence on A of the mean scattering cross sections, as well as of $\overline{\Gamma_n^0}/\overline{D}$, was calculated. The calculation was carried out for low-energy neutrons ($l = 0$) for nonspherical nuclei and for nuclei with a smeared-out boundary (see also References [75, 76]). Taking into account the smeared-out boundary (it was assumed that the potential falls off exponentially at the boundary of the nucleus) leads only to a small (by a factor of 1.5-2) proportional increase of the values of $\overline{\Gamma_n^0}/\overline{D}$ at the maxima and in the region between them. The comparison of results for nuclei with various degrees of elongation shows that with increasing elongation the maxima are shifted to positions corresponding to nuclei of bigger dimensions. This behavior of the function $\overline{\Gamma_n^0}/\overline{D}$ may explain the spread of the experimental values in the region $A \simeq 150$, since, according to [77] in this region the nuclei are highly nonspherical (Figure 11). The probable explanation for the large discrepancy in the values of $\overline{\Gamma_n^0}/\overline{D}$ for $A \simeq 70$ for even-even nuclei may be the fact that the sizes of these nuclei are smaller than those given by the simple equation $R = r_0 A^{1/3}$ and, therefore, the maximum of the function $\overline{\Gamma_n^0}/\overline{D}$ must be shifted towards higher values of A.

A detailed comparison of the results, calculated on the basis of the semi-transparent nucleus model, with the experimental data will enable the values of the real and imaginary parts of the optical potential to be ob-

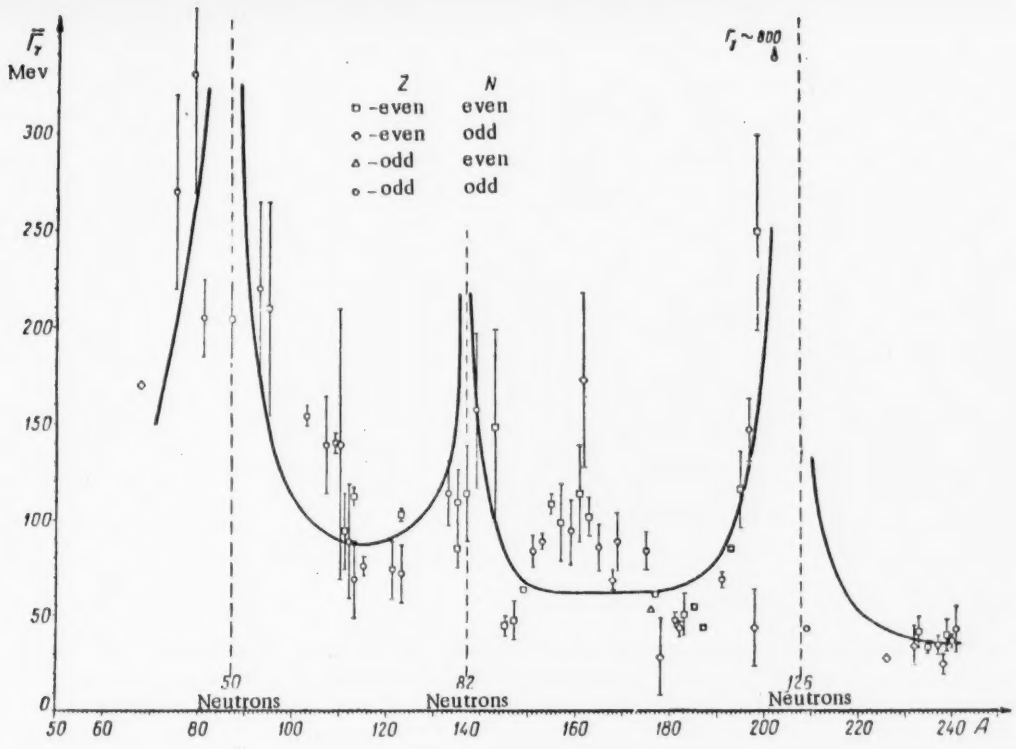


Fig. 13. The mean radiation width as a function of the atomic weight. Points give the experimental values; the full curve is the result of calculations of Reference [87].

tained more accurately. The value $\xi = 0.03$ for the ratio of the imaginary to the real part taken in the early work was subsequently increased to $\xi = 0.08$ [65] to explain the smeared-out nature of the maxima. The former value is in better agreement with the experimental results if the smeared-out nature of the nuclear boundary and the elongation of nuclei are taken into account.

Figure 12 shows the dependence of the mean separation between levels $\overline{D}$ on the atomic weight A. Statistical theory gives the relation between the level density $w(E^*)$ and the excitation energy E^* of the following form [78-80]:

$$w(E^*) = C \exp[2(aE^*)^{1/2}]. \quad (1)$$

In this equation the coefficients C and a depend in a complex manner on the numbers of protons and neutrons in the nucleus. For some values of odd A these coefficients have been calculated. The level density for 60 isotopes in the region of $A \approx 23$-209 was studied in Reference [81] for fission neutrons with an energy of ~ 1 Mev. The results of this work confirm the correctness of Equation (1) for nonmagic nuclei with a nuclear excitation energy of ~ 8 Mev.

Radiation widths are known for a considerably smaller number of levels and with less accuracy than the neutron widths. According to the independent-particle model the radiation widths for a particular nucleus must be approximately constant and show only statistical fluctuations, since the emission of radiation by a highly-excited nucleus can proceed through many intermediate states. It is possible that there is some dependence on the level spin, which does not contradict the statistical description of the radiation widths.

The authors of Reference [82] (see also [83, 84]), who collected the results of measurement of Γ_γ for 35 isotopes, came to the conclusion that the radiation widths for a given nucleus can be considered constant to an ac-

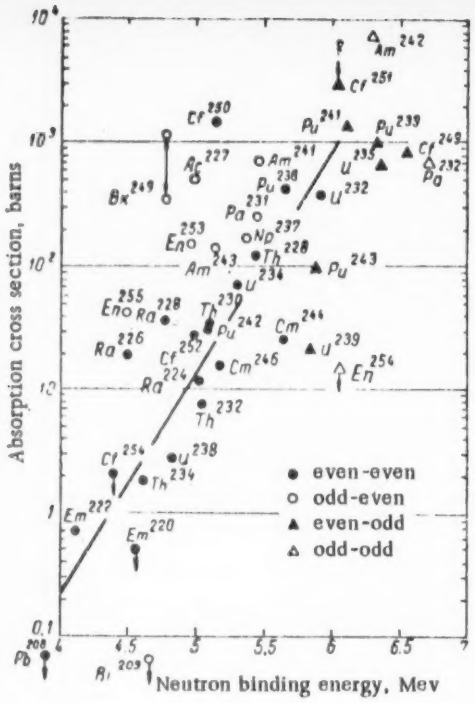


Fig. 14. The cross section for the absorption of thermal neutrons by heavy isotopes as a function of the neutron binding energy.

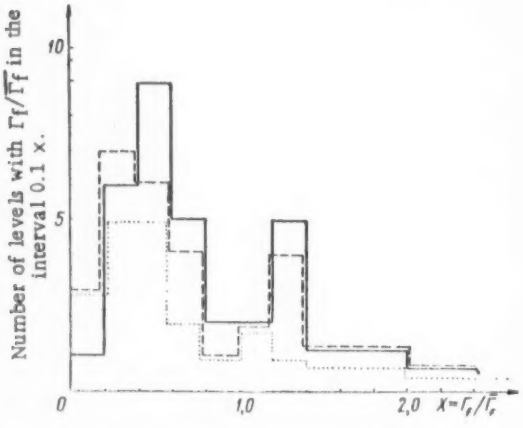


Fig. 16. The differential distribution of the fission widths of U^{233}, U^{235} and Pu^{239}, referred in each case to the mean value of the fission width. In addition to the values of Γ_f given in References [104] and [106], in the construction of the graph the data of Reference [23] were used for the total widths, assuming that the radiation widths are constant [104] (see footnote to Table 2). —— data of References [105, 43, 101, 104]; – – – – – data of References [104, 105]; . . . . . data of Reference [104].

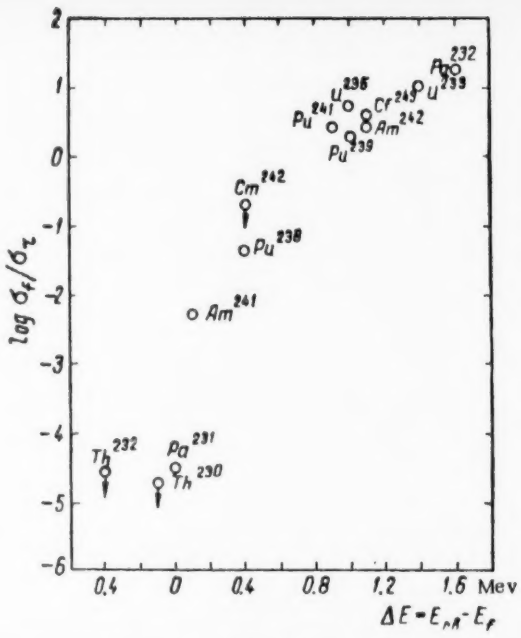


Fig. 15. The ratio of the fission to the capture cross section as a function of the neutron binding energy. The fission threshold E_f is equal to 5.3 Mev.

curacy of ~20%. In agreement with the theory given in [79] $\overline{\Gamma}_\gamma$ decreases with increasing A. In the vicinity of the doubly-closed shell at A = 208 an appreciable increase of $\overline{\Gamma}_\gamma$ by a factor ~10 is observed. A considerably less prominent maximum occurs near the closed neutron shell at A ≈ 140. This behavior of $\overline{\Gamma}_\gamma$ is in good agreement with the behavior of the separation between levels, $\overline{D}$, which also has maxima in the vicinity of closed shells.

The values of $\overline{\Gamma}_\gamma$ can be used for comparison with theory. In Reference [79], on the basis of the independent-particle model, the following evaluation of the radiation widths is given, corresponding to electric 2^l-pole radiation:

$$\Gamma_\gamma^l \sim \overline{C_l^2}\,\frac{e^2}{\hbar c}\left(\frac{R}{\hbar c}\right)^{2l}\frac{1}{D_0}\int_0^{E_n} E^{2l+1}\,\frac{D_l(E_n)}{D_l(E_n-E)}\,dE. \quad (2)$$

Here C_l is the matrix element for the transition; E_n the excitation energy of the level; $D_l(E_n)$ the separation between excited levels; $D_l(E_n - E)$ the separation between the lowest nuclear levels, which can take part in transitions of the type and order investigated; D_0 the energy of the first excited level. The width Γ_{Ml} for the magnetic 2^l-pole radiation is different from Γ_{El} by a factor of $10(\hbar/McR)^2$.

TABLE 2*

Some Parameters for Fissioning Nuclei

		$\bar{\Gamma}_f \cdot 10^3$ ev	$\bar{\Gamma}_\gamma \cdot 10^3$ ev	$\bar{D}$, ev	$2\pi\bar{\Gamma}_f/\bar{D}$
U^{233}	a	210	42 ± 8	0.93 ± 0.2	1.42
U^{235}	b	41		0.61 ± 0.05	0.42
	c	53	33 ± 6	0.63 ± 0.16	0.53
Pu^{239}	d	57		2.5 ± 0.6	0.16
	e	78	40 ± 8	2.61 ± 0.7	0.187

*The values of Γ_f are calculated as follows:

a) from the data of References [104, 105] and the values of Γ_f 260 ± ± 150; 15 ± 6 obtained from Reference [43] with the assumption that Γ_γ is constant [104];

b) from the data of Reference [43];

c and d) from the data of Reference [104];

e) from the data of Reference [101] and the values of Γ_f, 130 ± 50; 30 ± 10; 50 ± 15 obtained from Reference [43] with the assumption that Γ_γ is constant [104].

The values of Γ_γ are taken from Reference [104]. The values of D in rows a, b and d are taken from References [23, 43] and in rows a, c and e from References [104] and [106].

The experimental verification of the relation for the probability of radiation with a given multi-pole character and parity [85, 86] shows qualitative agreement with theory. However, the absolute values of the probabilities, calculated from Equation (2) with the assumption that $D_0 = 0.5$ Mev, are a 100 times bigger than the experimental values.

In Reference [82], using Equation (2) for Γ_γ^l, as well as Equation (1) for the level density, the reduced radiation width $\bar{\Gamma}_{\gamma rw} = \bar{\Gamma}_\gamma (160/A)^{2/3} \times (6.5/E^*)^4$ is calculated as a function of the separation between levels D for an excitation energy E^* equal to the neutron binding energy. The best agreement with experimental data is obtained assuming that the transition is E1 and that $D_0 = 500$ Mev. On this basis the authors conclude that electric dipole transitions are the most probable with the radiation capture of a neutron. However, it must be pointed out that the necessity for the choice of D_0, so large by comparison with the actual separation between the lower levels, seems to be rather strange and is apparently connected with the inadequacy of the theory.

In Reference [87] an evaluation of the matrix element in Equation (2) is carried out with the help of the experimental data on $\bar{\Gamma}_\gamma$, $\bar{D}$ and E^*. The results of the calculation, shown in Figure 13, are in good agreement with the experimental data.

The authors of References [88] and [89] have collected the data on the cross sections for absorption of thermal neutrons with the aim of discovering their dependence on the various nuclear constants, and to compare the experimentally-determined values with the theoretical. The absorption cross section for thermal neutrons, σ_{aT} in barns, can, according to Reference [79], be written in the approximate form

$$\sigma_{aT} = \left(\frac{\xi^2 \Gamma_\gamma}{\bar{D}}\right) \cdot 1100, \qquad (3)$$

where ξ^2 is a factor of the order of unity, and Γ_γ and $\bar{D}$ are defined above.

From the graph, given in Figure 14, it is seen that the best agreement of Equation (3) with experimental data is observed for the even-even nuclei. However, the growth of the cross section with increasing excitation

energy E^* is appreciably bigger than is expected from the semi-empirical relation (3). Harvey [89] points out that this discrepancy can be partially explained by a systematic error in the measurements of σ_{aT}, determined by the fact that actually the measurements are carried out over the whole of the spectrum of reactor neutrons which include nonthermal neutrons, and the contribution of resonance neutrons will be larger for the larger cross sections. However, this effect is not sufficient to explain the discrepancy.

The theory of fission, within the framework of the liquid-drop model [90, 91], cannot predict the magnitude of the width of an individual fission resonance Γ_f. Such a model gives only a qualitative description of some of the peculiarities of the fission mechanism, for example, the asymmetry in the mass distribution of fragments [92, 93].

The mean fission widths of levels $\overline{\Gamma_f}$ can be evaluated on the basis of the statistical model of the nucleus. In Reference [90] the following expression for $\overline{\Gamma_f}$ is given:

$$\overline{\Gamma}_f = \frac{\overline{D}}{2\pi} N,$$

where $\overline{D}$ is the mean separation between the fission levels, and $N \geq 1$ is the effective number of channels available at a given excitation. At the present time, it can be considered established that the resonances found in the total cross section of the odd uranium and plutonium isotopes are present also in the fission cross section. Therefore, for the evaluation of $\overline{\Gamma_f}$ it is advantageous to use the values of $\overline{D}$ calculated with the measured total cross sections, since the latter have been measured in a considerably bigger energy interval and are therefore more accurate.

Data on the mean widths of $\overline{\Gamma_f}$, $\overline{\Gamma_\gamma}$ and the mean separation $\overline{D}$ for U^{233}, U^{235} and Pu^{239} nuclei are given in Table 2.

The fission width $\overline{\Gamma_f}$ in U^{233} is appreciably bigger than in U^{235} and Pu^{239}. This can be explained by the fact [64] that the binding energy E_B is bigger for U^{233} than for U^{235} and Pu^{239}, while the fission threshold E_f is approximately the same. This correlation between the level width and the binding energy is confirmed by the experimentally established data on the dependence of the fission cross section σ_f on the difference $E_B - E_f$ [94].

From Figure 15 it follows that with increasing difference $E_B - E_f$ the ratio of the fission cross section σ_f to the capture cross section rapidly increases. However, the assumption used in the construction of the graph that the fission threshold $E_f \sim 5.3$ Mev is constant for all nuclei is not altogether accurate [95], which makes the comparison less reliable. From Table 2 it is seen that for all three nuclei the mean fission width $\overline{\Gamma_f}$ is approximately equal to the mean radiation width $\overline{\Gamma_\gamma}$, but is considerably bigger than the reduced neutron width $\overline{\Gamma_n^0}$. In a number of experiments [96-99, 43, 100-103] it was established that the individual widths Γ_f fluctuate strongly by comparison with the mean width $\overline{\Gamma_f}$, and therefore the distribution of fission widths resembles the distribution of neutron widths more than that of the radiation widths. In References [97-99] the integral distribution of U^{235} and Pu^{239} fission widths is described by the random-distribution law $\exp(-x)$, where $x = \Gamma_f/\overline{\Gamma_f}$; in [64] and [102] the distribution of U^{235} fission widths is in better agreement with the expression $\exp(-x^2)$. In other References [43, 62, 101], it is pointed out that the fission widths have a tendency to group together. Figure 16 shows the differential distribution of fission widths for U^{233}, U^{235} and Pu^{239} according to the data of References [43, 101, 104, 105]. It can be assumed that there exist two systems of levels, each of which corresponds to one of the two possible orientations of the neutron spin relative to the spin of the nucleus. However, because of the large statistical errors of the measurements a reliable conclusion cannot be made. If there is a connection between the spin of the compound nucleus and the level width Γ_f, then probably it can be confirmed by measuring the yield of masses from levels with different widths Γ_f [107]. It is possible that one system of levels gives an appreciably higher probability for symmetrical fission than the other system. From experiments on the fission of nuclei by fast neutrons and on photofission [108] it follows that the symmetrical part of curve giving the mass yield is very sensitive to the excitation energy.

An interesting experimental fact for the fission theory is the anomalous form of some low-energy resonances in the fission of U^{233} and U^{235} [37, 96, 100] which are not described by the Breit-Wigner single-level formula. In Reference [96] the deformation of the 1.14 ev level in U^{235} is explained by the effect of the interference between fission resonances which have the same spins. Other authors [62, 103] assume the existence of weak levels overlapping the anomalous levels. The experimental curve for the total cross section of U^{235} up to an energy of 1.5 ev

is in good agreement with that calculated from the Breit-Wigner formula assuming the presence of two weak levels with energies 0.42 and 0.91 ev. The distortion of the shape of the levels can be explained also by assuming the existence of a mechanism of nonresonance fission analogous to potential scattering, which interferes with the resonance fission. Further, more accurate measurements will obviously lead to more reliable information on the reason for the distortion of the shape of the levels.

In Reference [109] (a small fission resonance in Pu^{240} was found) it is shown that the fission width Γ_f is not negligibly small by comparison with the radiation width Γ_γ in the case of even-even nuclei. The terminal value of the fission width of the level with an energy of 1.06 ev in Pu^{240} indicates that the mechanism of sub-barrier fission of even-even nuclei exists, and that it must be taken into account in the evaluation of the fission cross section below the threshold [90-92].

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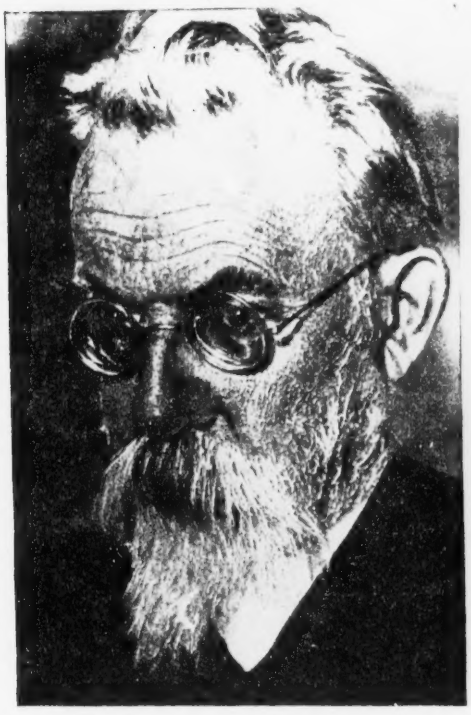
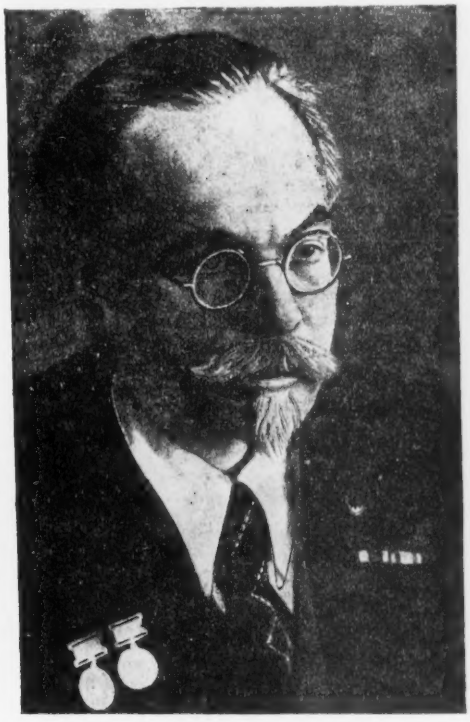
SOVIET RADIOCHEMISTRY

A.N. Murin

Work on the investigation of radioactive materials was begun in this country soon after the discovery of the phenomenon of radioactivity by Becquerel in 1896.



V.I. Vernadskii



V.G. Khlopin

At the very beginning of the 20th century, A.P. Sokolov (Moscow University) and I.I. Borgman (St. Petersburg University) investigated the radioactivity of natural objects – medicinal muds, water, rocks and the air of the atmosphere. A.P. Sokolov also introduced a series of essential improvements in methods of radioactivity measurements and, in particular, developed the well-known compensation method for determining radium by radon. Iu.N. Antonov, known for the discovery of uranium-Y (1912) and L.S. Kolovrat-Chervinsky, who investigated the emanating capacity of solid and molten salts, should also be noted among the Russian radiologists of the pre-Revolutionary epoch.

The work of individual Russian scientists, often done abroad, is not sufficient justification to talk of the existence of radiochemistry as a science in pre-Revolutionary Russia. One of the reasons for the lack of develop-

ment of radiological investigations was the absence of radium and other radioactive elements. This situation was clearly realized by the outstanding Russian scientist V.I. Vernadskii, who organized an investigation of the radioactive minerals of Russia. The Radium Commission of the Academy of Sciences was created in 1909. However, all the attempts of V.I. Vernadskii to organize the radium work on a large scale were frustrated by insufficient means and incomprehension of the seriousness of the problem.

The Radium Commission of the Academy of Sciences met with a completely different attitude on the part of the Supreme Soviet of the national economy, established after the Great October Revolution, which decided in April 1918 to establish a plant for the extraction of radium from native raw materials. Despite the difficulties arising from post-war disorder and civil war, V.G. Khlopin was able to obtain highly active radium preparations for the first time in this country in 1921.

In 1922, V.I. Vernadskii and V.G. Khlopin founded the Radium Institute of the Academy of Sciences of the USSR, thus consolidating the beginnings of Soviet radiochemistry.

Radioelements in physicochemical systems. Some of the first work carried out by V.G. Khlopin and his colleagues was devoted to the development of a method for fractional precipitation of radium-barium salts. In 1924, generalizing on the results of Laboratory and factory work, V.G. Khlopin established that the distribution of radium between crystals and mother liquor occurs in accordance with the Berthelot-Nernst law, which was found to be applicable in systems in which the component "guest" (in this case, the radium halide), in a state of high dilution, is isomorphous to the "host" crystals (barium halide). Later, V.G. Khlopin and his student, B.A. Nikitin, put forward the hypothesis that the fulfillment of the Berthelot-Nernst-Khlopin law in the case of the distribution of some microcomponent in solution-precipitate, precipitate-gas systems, is proof of the presence of complete isomorphism between the corresponding compounds of "guest" and "host."

In agreement with the relation obtained by A.P. Ratner, the value of the distribution coefficient of the microcomponent is determined by the difference in the chemical potentials of the ion in question in a pure and mixed crystal and by the activities of saturated solutions over pure crystals of macro- and microcomponents. Investigations in recent years, carried out in the USSR [1] and abroad, have shown that this relation is essential for studying the thermodynamics of isomorphous mixed crystals.

V.G. Khlopin and his colleagues – A.E. Polesitskii, A.P. Ratner and P.I. Tolmachev – studied the mechanism of equalization of the microcomponent concentration in the crystalline phase and showed that it occurs by recrystallization of the solid salt.

An investigation of the distribution of radium between the melt and crystals of suitable isomorphous salts showed,also, that in this case, too, the distribution was controlled by recrystallization of the precipitate.

Considerable investigations of the problems of coprecipitation carried out in the Radium Institute of the Academy of Sciences of the USSR [3], using extensively not only natural but also artificial radioactive elements (among them the transuranics – neptunium, plutonium and americium), substantially expanded our understanding of the mechanism of formation of various types of mixed crystals.

The existence of a concentration limit, below which mixed crystals cannot be formed, was found for "Grimm" crystals anomalous mixed crystals [4]. Besides the anomalous mixed crystals, which have a lower limit, systems with Pu^{+4} and Np^{+4} (as microcomponents) and $K_3La(SO_4)_3$, K_2SO_4 (as macrocomponents) were discovered whose crystallization coefficient remains constant even at concentrations of the order of 10^{-9} M [5].

The problem of the peaceful use of atomic energy has required that Soviet radiochemists develop extraction and sorption methods for isolating radioelements.

The results of detailed investigations of the mechanism of extraction of radioactive isotopes from aqueous solutions with organic solvents [6] made it possible to formulate certain general conclusions on the relation between the structure of the organic solvents investigated and their extraction capacity. By widely applying the spectrophotometric method, the states of a series of radioactive elements in anhydrous solutions were determined. Recently, the extraction method's field of application has been expanded to include transplutonic elements.

The adsorption of radioelements on crystalline precipitates, glass, charcoal, silica gel and other adsorbents has been investigated [7]. The investigation of polonium adsorption on various adsorbents [8] first showed the actual existence of radio-colloids. The conditions of formation of radio-colloids were further investigated [9], si-

multaneously using various experimental methods (electrochemistry, ultrafiltration, centrifuging, radiography, etc.).

Many laboratories in the Soviet Union investigated the processes of ion-exchange and chromatographic separation of radioelements.

Moreover, the separation of uranium and thorium over a wide range of thorium concentrations was investigated, a chromatographic purification of various solutions of zirconium and niobium from microquantities of impurities was developed [10] and selective adsorption of certain radioelements was also studied on ion-exchange resins, silica gel, activated charcoal in hydrogen and oxygen atmospheres and other porous adsorbents [11].

A method for investigating the processes of complex-formation in solution by simultaneous absorption of the central ion by an anionite and a cationite was developed [12]. Using this method, the state of microquantities of a series of fission products – zirconium, niobium, yttrium – were investigated in mineral and organic acid solutions. Methods for the chromatographic separation of rare earth and transuranic elements were improved considerably [13]. Moreover, home produced synthetic resins were used successfully; work with highly active preparations was carried out on automatic equipment.

Chemistry of radioelements. The investigation of emanation distribution in the systems Rn – $H_2S \cdot 6H_2O$, Rn – $SO_2 \cdot 6H_2O$, Rn – $H_2S \cdot 3C_6H_5OH$, Rn – $H_2S \cdot 2C_6H_5CH_3$, Rn – $H_2S \cdot 3ClC_6H_4OH$ and others made possible not only the preparation of some intert gas compounds (using isomorphous coprecipitation), but also the determination of their composition [14]. Using the unequal stabilities of different inert gas hydrates, the quantitative chemical separation of radon from helium, neon from argon, and later, argon from helium and neon were accomplished.

Until recently, due to the lack of weighable quantities of polonium at the disposal of investigators, the study of the chemical properties of this element was carried out with only indicator amounts and using mostly the method of isomorphous cocrystallization. It was thus [15] that polonium compounds with −2 and +6 valency were first identified and organic compounds of divalent polonium prepared: the methyl and benzyl derivatives, corresponding to analogous tellurium compounds. Furthermore, an organic derivative of tetravalent polonium, $(CH_3)_2PoI_2$, was synthesized [16].

Investigations on the electrochemistry of polonium were begun in 1946 [17], when a method was proposed and developed for determining the electrode potentials of radioelements by an unusual modification of Hevesy and Paneth's method; the potentials of polonium precipitation on gold and platinum were defined more accurately, the valencies of polonium for the normal and reduced states (+4 and +2 respectively) determined and the forms of its ions in certain compounds investigated. The disproportionation of tetravalent polonium was also established and the electrode potentials of hexavalent polonium investigated.

The problems of uranium and thorium chemistry have a quite special position in radiochemistry, as these elements are found in weighable amounts in any chemical laboratory and are therefore amenable to classical methods of analysis. The number of investigations carried out in this field are extremely numerous: we will mention only a few of them.

Various methods, spectral, x-ray spectral, polarographic, luminescent, activation, etc., were developed for uranium analysis. Moreover, special attention was paid to the creation of straightforward physicochemical methods of determining uranium and impurities in it without preliminary chemical separation [18].

Substantial results were achieved in the inorganic chemistry of uranium and thorium. A series of salts of a complex acid of the type $H_4[U(C_2O_4)_4]$ were synthesized and the physicochemical properties of the compounds prepared investigated. It was shown that the acidic properties of uranium oxalate hexahydrate were expressed considerably more strongly than those of the analogous thorium compound. A method of U(VI) reduction with rongalite was developed [19]. The conditions of existence were established for a series of peracidic uranium compounds, which form in the system $UO_2(NO_3)_2$ – NaOH – H_2O_2 – H_2O and their simplest formulas were given: $H_2U_2O_9$, $HU_2O_9^-$, $U_2O_9^{-2}$, UO_6^{-2}, HUO_8^{-3}, UO_8^{-4}, $Na_2U_2O_9 \cdot 6H_2O$ and $Na_8U_4O_{22} \cdot 3H_2O$ [20].

The chemistry of uranium oxides and some halides was studied. A series of investigations on the photochemistry of aqueous solutions of uranium and thorium salts was completed [21].

Among numerous works on the chemistry of other radioelements, the following should be noted: a new method for the rapid determination of proactinium with zirconium mandelate, which ensures complete separation

of protactinium from all natural α-active radioelements [22], an investigation of the valency state of technecium and the development of a method for its separation [23] and finally, the development of a sulfate method for plutonium and neptunium separation [24]. Soviet investigators developed methods for the separation of neptunium and plutonium [25] and also americium from fission products [26],and the chemical properties of plutonium, americium and curium were investigated [27].

The coprecipitation method was used for studying the chemistry of these elements in indicator amounts. Spectrophotometry was used to investigate the formation of complex plutonium and americium ions in inorganic acids; electromigrational and electrochemical investigations were carried out. In addition to that, Am(VI) self-reduction and Am(V) disproportionation were observed.

Numerous examples of the use of radioactivity in chemical investigations are given in the article "The Use of Radioactive Isotopes in the USSR" (see p.2345 of this journal). Therefore, we shall only mention here work on the Szilard-Chalmers effect, in which the changes in the chemical state of elements in nuclear reactions (n, γ) and (γ, n) and nuclear conversions (β-decay, isomeric transition, etc.) were investigated; effective methods for the concentration of radioactive isotopes of silicon, phosphorus, chromium, germanium, arsenic, molybdenum, indium, tin, antimony, tungsten, rhenium, mercury, bismuth and tellurium were developed; original methods for the isolation of isomers and synthesis of labelled molecules were worked out [28].

Chemical methods for investigating nuclear reactions. Investigations related to the explanation of the chemical nature of fission products were begun in the USSR before atomic nuclear fission was discovered. Soon after the first work by Fermi on the use of neutrons for the production of artificial radioactive elements, the inert gases xenon and krypton were discovered among the fission products [29] and the products of thorium fission by neutrons were studied [30]. In 1947, the gaseous products of spontaneous fission of uranium nuclei were found in uranium minerals [31].

During recent years the phenomenon of fission, with the wide application of chemical methods, was investigated very intensively. Fission products, formed by the irradiation of atomic nuclei not only with neutrons but also with γ-quanta [32] and heavy ions were investigated. The radiochemical study of fission products of atomic nuclei found in the atmosphere, atmospheric deposits, rocks and soils were of great importance from the theoretical and practical points of view. As a result of systematic investigations it was found that, at the present time, long lived radioactive nuclides are accumulating in the atmosphere, soil and small open reservoirs.

Mass-spectrometric methods of determining the yields of fission reaction products of uranium and plutonium isotopes were, likewise, considerably developed, which substantially speeded up analysis and increased its accuracy [33].

Radiochemical investigations of the reactions of protons with energies of up to 680 Mev with complex nuclei were begun right after the starting of the large synchrocyclotron of the United Institute for Nuclear Investigations. The investigations covered the atomic nuclei of a wide range of atomic and mass numbers (aluminum, copper, silver, lanthanum, tantalum, tungsten, bismuth, thorium, uranium); the quantitative and qualitative rules governing the processes of deep splitting and the nature of fission with fast particles were clarified [34]; the fission of silver nuclei was discovered and the effect of the shell structure of the product-nuclei on the magnitude of the yield; a relation was found between the distribution of nuclei formed and the isotopic composition of inert gases arising in meteorites due to the effect of cosmic radiation; the process of fragmentation was studied, etc. Many radioactive isotopes, mainly neutron deficient ones, that had previously been unknown, were discovered and identified. The spectra of nuclides formed were thoroughly investigated by magnetic and scintillation γ-spectroscopy [35]. Decay schemes were established for a series of nuclides, showing the quantum characteristics of the energy levels; the results obtained were compared with contemporary theories on the structures of complex nuclei.

It is impossible to note in a short review all the scientific directions which are being vigorously developed in the USSR. The growth of the scientific production of Soviet scientists in the last two to three years shows that our native radiochemistry, which is so closely related to a number of industries and to medicine, biology and agriculture, will continue in the future to promote the development of atomic science and multiply the possibilities of its peaceful use.

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THE USE OF RADIOACTIVE ISOTOPES IN THE USSR

G.V. Kurdiumov, M.B. Neiman and G.M. Frank

Natural radioactive isotopes first came into use in the Soviet Union soon after the October Revolution. E.S. London and other scientists and physicians used natural radioactive elements in the treatment of cancer; V.I. Vernadskii, V.G. Khlopin, I.E. Starik and others [1] used them for determination of the age of minerals, and V.I. Spitsyn [2] used them for solving a number of problems in analytical chemistry.

Artificial radioactive isotopes were made in the USSR on the laboratory scale immediately after the publication of the paper by Curie and Joliot in 1934. The first paper to appear in the world literature on the use of artificial radioactive isotopes in chemical research was published in the USSR in 1935 [3].

After the Patriotic War, radioactive isotopes were made in the USSR by irradiation of targets in cyclotrons and nuclear reactors. In some cases targets containing pure stable isotopes are irradiated, so that the presence of undesirable impurities can be avoided. For example, the isotopes Fe^{59}, Fe^{55}, Ca^{45}, Sn^{123} and others are made by this method. Sr^{90}, Y^{90}, Ce^{144}, Cs^{137}, Pm^{147} and other isotopes which have extensive industrial uses are extracted from the fission products of fissionable materials.

The rate of growth of radioactive isotope production in the USSR is seen in Figure 1, where data are given, as an example, for the growth of the production of C^{14} and Co^{60} isotopes in 1953-1957, and for the numbers of consignments of radioactive isotopes sent to China, Czechoslovakia, Poland, Hungary, Rumania, the German Democratic Republic, Bulgaria, and certain other countries, and also used in the USSR.

In 1957, the USSR industry produced 75 different radioactive isotopes and a large number of different compounds tagged with radioactive isotopes.

The increased production of isotopes and measuring equipment was accompanied by an extension of the number of laboratories using radioactive isotopes in scientific and technological research. Several specialized laboratories were established for the application of radioactive isotopes in chemistry, industry, instrument production, agriculture, biology, and medicine. Many laboratories, scientific research institutes, and centers of higher education in Moscow, Leningrad, Kiev, Gor'kii, Khar'kov, and Minsk use radioactive isotopes in their work. Since 1949 a number of laboratories in institutes and industrial undertakings of the Uzbek, Kazakh, Latvian, and other Union Republics have been using the tagged atom technique.

An important role in training research workers has been played by the organization of practical training courses in isotope work for engineers, chemists, biologists, and physicians, held in institutes of physics, physical chemistry, biophysics, and some others.

Within the limits of this article it is impossible not only to describe the results obtained by the diverse uses of isotopes, but even to list the names of the numerous workers who have done much to develop this field and who have obtained interesting and important results. We shall therefore restrict ourselves to mentioning some of the most important investigations in the fields of chemistry, industry, biology, medicine, and agriculture.

Radioactive isotopes in chemistry. Artificial radioactive isotopes were used for chemical research in the USSR before they were used for this purpose in other countries. In 1935-1938 papers were published, which marked the start of an extensive series of researches on the isotope exchange of halogens and the mechanism of catalytic processes [3, 4].

Before the Patriotic War, chemical research with the use of artificial radioactive isotopes was concentrated

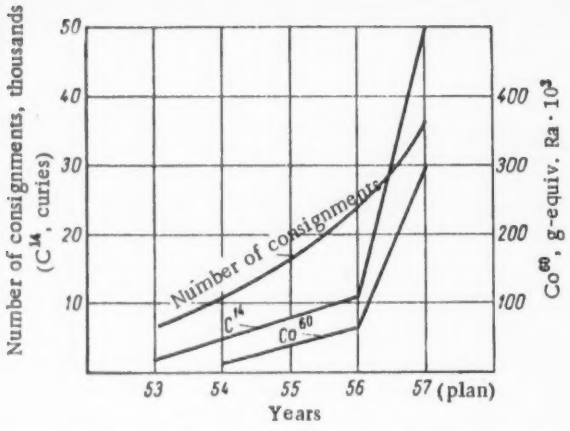

Fig. 1. Growth of radioactive isotope production in the USSR.

in Leningrad, and was carried on in the Radium Institute, the Institute of Chemical Physics, and Leningrad University. After the war the range of this work was extended considerably, and it now includes a large number of investigations.

In the field of inorganic chemistry, systematic work has been in progress for many years on studies of the mechanism of isotope exchange in complex platinum compounds [5]. The easier exchange of the added groups in comparison with the exchange of central atoms, and the increased exchange rate of the atoms in the added groups with increased thermodynamic bond strength were confirmed by a number of foreign investigations.

Numerous authors [6, 7] have studied the isotope exchange of bromine between the bromides of a large number of elements and elementary bromine, and the exchange of sulfur with polythionates.

As the result of his own investigations and those published in the literature, A.I. Brodskii concluded that isotope exchange reactions may proceed by either a dissociation or an association mechanism.

I^{131} was used to demonstrate the equivalence of iodine atoms in the HgI_4^{--} anion. The equivalence of the bromine atoms in $HgBr_4^{--}$, and also in $TlBr_3$, PBr_3 and PBr_5 was demonstrated by means of Br^{82} [8].

The S^{35} radioactive isotope was used to study the mechanism of thiosulfate formation in the interaction of H_2S, SO_2 and NaOH. It was shown [9] that the central sulfur atom in thiosulfate is formed from SO_2, while the peripheral sulfur comes partly from H_2S (two-thirds) and partly from SO_2 (one-third).

In a study of diffusion rates of the components in inorganic salt crystals [10] it was shown that in a number of cases the diffusion rates of the cation and anion differ by many orders of magnitude. Continuation of this work led to the development of a theory of diffusion exchange in solid-gas, solid-melt, and solid-solution systems.

Researches [11] on the self-diffusion of iron in binary alloys, which showed that the diffusion rate falls sharply on formation of chemical compounds, led to the development of a new method of physicochemical analysis, based on the use of diagrams for the variation of the diffusion coefficient with the composition of the alloy. Inflection points on the diagrams correspond to formation of chemical compounds in the alloys.

Soviet investigators have obtained a number of important results in the application of radioactive isotopes in analytical chemistry. The two main advantages of the radioactive tracer method are used here: its enormous sensitivity, and the possibility of analysis without separation.

Tagged atoms have been used to find suitable conditions for the analysis of substances of similar chemical properties. For example, it was found with the aid of radioactive bromine and iodine isotopes that separation of iodides and bromides by oxidation with nitric acid gives quantitative results [12]; the use of Ca^{45} showed that the oxalate method for separation of calcium and magnesium involves considerable errors [13]; Sr^{90} and Ba^{140} were used to find conditions in which the chromate method for the separation of these elements gives good results [14].

A large series of researches on coprecipitation in gravimetric analysis with the use of inorganic and organic reagents has been completed [15].

An original method of adsorption on carbon for the separation and purification of radioactive isotopes has been developed. A series of investigations dealt with studies of extractive separation with the use of radioactive tracers [15].

Radioactive isotopes were widely used for studying chromatographic separation of salts and gaseous mixtures [16]. Radioactivation methods have been developed for determination of ultralow concentrations of rare earth

metal impurities in various metals and graphite, and of copper, antimony, molybdenum, and zinc in metallic germanium and its oxide [17].

A number of new applications of the isotopic dilution method have been proposed and tested. An example is a method for determination of methyl, ethyl, and propyl alcohols in mixtures of these [18].

Soviet scientists carried out a large number of original researches with the use of radioactive isotopes in the field of physical chemistry. Radioactive isotopes were used successfully for determination of the vapor pressures of metals, salts, and oxides in the pure state and in mixtures [19]. Liquid-vapor equilibria for dilute solutions of acetic acid in water, ethyl acetate in carbon disulfide, and a number of other binary systems were studied. A new rapid method for solubility determinations was proposed, and numerous solubility determinations were carried out on a number of salts [20].

A series of important researches was carried out on theoretical and experimental aspects of isotope separation [21, 22].

In the field of chemical kinetics, Soviet scientists developed original methods for the application of radioactive isotopes to studies of the mechanism of homogeneous and heterogeneous reactions.

A kinetic isotopic method was developed [23] whereby it is possible to determine the sequence of formation of intermediate products in complex reactions, their formation and consumption rates and reaction orders, and to solve a number of other problems. This method is widely used in institutes of chemical physics, physical chemistry, and organic chemistry, in the Moscow and Saratov Universities.

A deuterium exchange method for identification of radicals in the hydrocarbon cracking reaction has been developed and applied [24]. A new method has been proposed for distinguishing between molecular, radical, and chain reactions by comparison of their rates away from equilibrium and in mixtures in thermodynamic equilibrium [25].

The rate of isotope exchange of halogen atoms and ions with alkyl halides of different structures has been studied with the aid of Br^{82} and I^{131}. The investigations showed that structural changes which accelerate ionic-molecular exchange reactions retard isotope exchange proceeding by a radical-chain mechanism [26]. It was shown that increase of pressure accelerates isotope exchange reactions in alcoholic solvents and retards the same reactions if ketones are used as solvents [27].

A very interesting case of inversion of the isotope effect was observed in the reduction of various metal oxides by tritium [28].

A series of original methods [29] has been proposed and developed for studying surface inhomogeneities with the aid of stable and radioactive isotopes, whereby it is possible to differentiate the influence of mutual repulsion and surface heterogeneity with respect to the nature of the adsorption isotherms and to adsorption and desorption processes [30].

The kinetics of a solid-phase reaction (vulcanization of rubber) was studied by observations of the diffusion rates of substances tagged with radioactive isotopes [31].

Radioactive isotopes were used to establish the equivalence of the nitrogen-carbon bonds in the tetramethylammonium ion [32], and also of bonds between sulfur and other atoms in organic and inorganic compounds [7]. Radioactive isotopes made it possible to determine the current density in conditions of stationary reversible potential between a metal and its ions in solution [33].

Radioactive and stable isotopes have been used very widely for studying reaction mechanisms in organic chemistry. Sites of bond formation and cleavage in esterification, hydrolysis, and aldehyde reduction were determined; the hydrogen regrouping effect was discovered; the allyl, phenol, and Beckmann rearrangements and some tautomeric changes were studied [8].

The heavy oxygen isotope was used to detect an error of method in Poliani's work, long regarded as classic, and a new irreproachable method was developed for determining the position of bond cleavage in the saponification of esters; it was shown by this method that different bonds may be broken in this reaction, depending on the structure of the acid and alcohol and the nature of the saponifying agent [34]. Hydrogen exchange of a number of organic compounds in liquid ammonia and liquid HBr was studied and it was shown that the exchangeability of

different hydrogen atoms varies greatly with the solvent [35]. Tagged atoms were used in Gor'kii Institute of Chemistry [36] for studying the decomposition of pentaphenylphosphorus and the mechanism of certain reactions of organometallic compounds. It was shown with the aid of Hg^{203} [37] that configuration inversion occurs in electrophilic substitution involving one of the bonds of a carbon atom.

Radioactive isotopes have also come into extensive use for control in chemical industry and for studying the mechanisms of a number of industrial processes [38]. The pyrolysis of ethane was studied in detail by addition of a small amount of methane tagged with C^{14} to it, and the constants for the series of elementary reactions which take place in this process were calculated [39].

The question of the participation of the oxygen present in catalysts in catalytic oxidation processes has been the subject of a number of studies. Radioactive isotopes were used for measurements of the surface of various materials used in the cement industry, of the surface of porous solids (by the emanation method), and for solving a number of other problems [40]. Ca^{45} was used for studying the structure of cement clinker [41], etc.

Radioactive isotopes in technology. Radioactive isotopes are widely used in various branches of technology and technical sciences: in metallurgy, metallography, machine design and construction, instrument construction, power engineering, power mechanics, and in prospecting for and developing mineral products. Isotopes have been used as sources of penetrating radiation and as tagged atoms.

The appearance of a cheap source of γ-radiation in the form of Co^{60} has made it possible to introduce quality control of various kinds of metallic products, rapidly and on a large scale. The high penetrating power of the γ-radiation of Co^{60} makes it possible to reveal internal flaws in steel articles up to 300 mm thick, whereas with the use of x-rays steel even only 80-100 mm thick presents considerable difficulties. Co^{60} is now being used for the control of the quality of articles and constructions in many undertakings of the aviation, shipbuilding, metallurgical, machine building, and chemical industries [42-45]. Other isotopes (Ir^{190}, Cs^{137}, Tu^{170}) giving less hard radiation are also used; these are more suitable for use with small thicknesses of metal.

In addition to the photographic method, ionization methods of flaw detection, developed in the Institutes of Metal Physics of the Urals Branch of the Academy of Sciences and of the Central Scientific Research Institute of Ferrous Metallurgy and in other institutions, are coming into use; with these methods it is possible to carry out continuous control, for example of welded joints, without the expenditure of costly x-ray film. Radiation is recorded in these methods by means of γ-quantum counters [45, 46].

Radioactive isotopes are used in instruments for the control of various technological parameters and processes [47]. The absorption and scattering of radiation passing through substances are utilized for control of sheet and band thickness during rolling processes, control of coating thickness, measurements of density and of the levels of liquids and granular solids in closed vessels, for counting articles moving along a conveyor, for measuring tube wall thickness, etc. Liquid level meters are used, for instance, for control and automatic regulation of the liquid metal level in continuous teeming of steel. The use of radioactive isotopes for quality control and regulation of technological processes in various branches of our industry results in considerable economic advantages.

In the development and industrial adoption of instruments using isotopes an important role has been played by the work of the Central Automation Laboratory, the Institutes of Physics, AN SSSR and Latvian SSR, the Institutes of Metal Physics of the Urals Branch of the Academy of Sciences and of the Central Scientific Research Institute of Ferrous Metallurgy, the Institutes of Automation and Telemechanics, AN SSSR, The Scientific Research Institute for Heat Engineering Instrument Construction, etc.

The interactions of nuclear radiations with matter are widely used for prospecting and development of mineral resources.

Radiation sources placed in boreholes emit scattered radiation which is recorded by counters. Strata with different minerals differ in their absorbing and scattering power according to their density and composition. This method has been developed and tested in some coal fields of the Union [73].

Radiometric methods are used on a considerable industrial scale in the oil industry [53, 56-58] for studying the geological structure of wells. A neutron source is placed in the well and the γ-radiation resulting from the action of the neutrons is recorded. Hydrogen-containing strata are identified by this method. Oil-bearing strata can be distinguished from water-bearing strata by the use of γ-spectrometers. These methods have been developed and introduced into production by the Institute of Petroleum of AN SSSR, the Central Scientific Research Institute

for Geophysical Prospecting Methods, the Gubkin Petroleum Institute, Moscow, the Mining and Geological Institute of the Urals Branch of the Academy of Sciences, etc. [57, 58].

The widest use of radioactive isotopes as tagged atoms has been made in the metallurgical industry [48-55]. Considerable contributions to the development of these methods and their adoption in works laboratory practice were made by the Institute of Metallography and Metal Physics of the Central Scientific Research Institute of Ferrous Metallurgy, the Institute of Metallurgy of AN SSSR, the laboratory of the Kuznetsk Metallurgical Combine and of "Azovstal'," the Stalin and Novo-Tul'sk Metallurgical Works, etc.

Studies of the blast furnace process have been made in two directions: investigations of the wear of the refractory lining of the hearth and shaft of the blast furnace, and studies of the motion of the burden and gases in the blast furnace [48].

Burning of the hearth was studied in several works by deposition of radioactive sources in different courses of the refractory blocks during major repairs to blast furnaces. All the iron and slag produced during the operation of the furnace was tested for radioactivity. The appearance of radioactivity in samples of metal or slags taken during tapping indicated burning of the hearth in the region of the source.

For determination of the rates of descent of the materials in the burden down the blast furnace, individual pieces of ore, coke, or limestone were "tagged." The passage of these pieces through a given level of the furnace was recorded by means of counters introduced into the furnace in water-cooled tubes [49].

The flow speed of gases through the blast furnace was measured by introduction of radon through the tuyeres with the blast, the radioactivity being recorded at the top of the furnace.

The results of the investigations of the blast furnace process are being used in work on improvement of blast furnace design.

In the field of steel smelting, a considerable number of investigations on the thermodynamics of the distribution of phosphorus, sulfur, chromium, molybdenum, and tungsten between iron and slags of different compositions have been carried out in the Central Scientific Research Institute of Ferrous Metallurgy. The coefficients of distribution of phosphorus, sulfur, chromium, molybdenum, and tungsten as functions of the steel and slag composition and temperature were determined for the first time by measurements of the radioactivity of metal and slag samples taken when the system reached equilibrium.

Radioactive isotopes are used with success for studying the thermodynamic properties of solutions of sulfur, phosphorus, chromium, silicon, and other elements in liquid iron. Such investigations have been carried out both by measurements of the partial pressures of the elements over liquid iron, and by a new method based on measurements of the radioactivity of refractories in contact with molten iron containing the element in question.

The use of radioactive isotopes proved especially suitable for studying the kinetics of phosphorus and sulfur transfer from the metal to the slag; this is very important for developing methods for the production of iron and steel with the lowest possible concentrations of these harmful impurities. Kinetic equations for the dephosphorization and desulfurization of iron and steel have been derived [32], and the factors governing the rate of removal of impurities from the metal have been determined. The kinetics of desulfurization in electric arc furnaces was studied with the aid of S^{35}.

The kinetics of iron isotope exchange in conditions of equilibrium between the metal and slag (with Fe^{59} previously added to the slag) was investigated in order to find the rate-determining reaction step in the metal-slag binary system. It was found that in the reaction of iron isotope exchange between the slag and liquid metal the slowest step is diffusion in the slag phase, while if the system is agitated, the slowest step is mass transfer in this phase.

Studies of iron exchange and distribution between the slag and the steel melt in works conditions made it possible to derive an exchange reaction scheme based on the concept of diffusion as the rate-determining step.

The distribution of tungsten between the metal, slag, and gas phase was studied at the Kirov Works.

The use of Ag^{110} at the Cheliabinsk Metallurgical Works made it possible to show that the main cause of faults (phase separation and scabs in pipes) is turning of the skin on the metal in casting, and to work out effective measures for its prevention.

Radioactive isotopes were used for developing a method for the determination of transport numbers of ions in mixtures of melted oxides, based on measurements of the very small changes of concentration which occur in melts when a small quantity of electricity is passed through them. It was found that in liquid silicates and phosphates electricity is transported exclusively by cations. Measurements of transport numbers of cations in melts with two cations made it possible to determine relative mobilities of cations.

One of the most important tasks of high-grade metallurgy is the production of steel with the minimum content of nonmetallic inclusions. To solve this problem it is necessary to install sources from which nonmetallic inclusions enter the steel during smelting and teeming. In a number of works Ca^{45} was used for "tagging" the linings of the ladles, troughs, bottom-casting equipment, and the slag, in order to study this question. Subsequent isolation of inclusions from the finished steel and determination of their radioactivity gives an indication of the sources of contamination of the metal.

Studies of the nature of slag inclusions in boiling steel showed they originate both by incorporation of slag floating on the metal surface in the mold, and by attack on the bottom-casting ducts. As a result, technological measures were developed whereby the amount of spoilage has been reduced considerably.

Studies of the hydrodynamic state of the liquid phases in the Martin furnace are of practical importance, as this is directly related to heat exchange processes in the steel, floating of nonmetallic inclusions, solution of alloying additions, and degasification. Mass transfer processes in Martin furnaces have hitherto been studied by indirect methods only. In a number of foundries Co^{60} has been used as tracer for studying the movements in liquid steel; this tracer remains completely in the metal phase during smelting. The rate of movement of the metal was estimated from measurements of the radioactivity of metal samples taken from the surface of the steel melt. The results showed that at high rates of carbon oxidation the movement of the metal is turbulent in character.

The isotopic dilution method was used for determining the rate of scrap melting and the rate of slag formation in Martin furnaces [51].

It was found that both processes conform to the same kinetic equation, according to which the rates of melting and slag formation are proportional to the weight of solid scrap or limestone respectively, raised to the power of two-thirds.

The effect of the order in which the charge materials are introduced on the rate of melting of the metallic charge in Martin furnaces was studied in the Magnitogorsk Metallurgical Combine.

Radioactive isotopes were used for studying the crystallization kinetics of steel in molds, in order to determine the actual rate at which the solid phase boundary moves through the solidifying steel and to find the influence of the crystallization rate on the distribution of the elements in the ingot. The position of the solid phase boundary was determined by means of consecutive additions of P^{32} and S^{35}, which dissolve in steel, introduced while the steel was cooling in the mold.

Work has recently been started on the use of radioactive isotopes for rapid analysis and checking the accuracy of chemical methods of analysis. At the "Azovstal'" Works a rapid method for determination of phosphorus pentoxide in slags during phosphorus reduction has been developed, based on the introduction of a small amount of P^{32} into the iron.

A characteristic feature of this method is that extremely small amounts of P^{32} are used (of the order of 0.04-0.05 microcurie per 1 ton of metal). This can be done because the radioactivity is determined in large samples of slag, by means of four counters connected in parallel.

A similar method was used for rapid determinations of phosphorus in the metal in the development of a new process for converter reduction of Martin pig iron.

Numerous investigations with the use of radioactive isotopes were carried out in order to study the phenomena occurring in metals and alloys in the solid state.

Tagged atoms made it possible to study the rate of movement of atoms among atoms of the same kind (self-diffusion), and its dependence on the temperature. Studies of self-diffusion and diffusion are particularly important for a deeper understanding of the nature of interatomic bonds, phase transitions, and processes which occur in metals and alloys under load at high temperatures. The first use of radioactive isotopes for this purpose was in

the Soviet Union, where self-diffusion in gold was studied by means of a radioactive isotope as early as 1937 [59].

A considerable number of studies have been devoted to the development of various methods for measurement of diffusion coefficients with the aid of tagged atoms.

An enormous amount of experimental material on self-diffusion and diffusion in high-melting metals and alloys, which is of great scientific and practical importance, has now been accumulated. It has been found that alloying elements may have a significant influence on self-diffusion of the base metal atoms [53, 60-62]. These results are important for interpretation of the processes which occur in alloys at high temperatures, for development of a theory of alloy formation, and in the search for new alloys.

An important result achieved by the use of tagged atoms is determination of the role of internal grain structure in self-diffusion and diffusion processes; this gave insight into the nature of the influence of preceding phase transitions on the properties of alloys at elevated temperatures [62], and also led to a better understanding of the mechanism of diffusion [63].

Microradiography is used for studying inhomogeneities in the macro- and microstructure of metals and alloys, and peculiarities of diffusion phenomena at grain boundaries.

Microradiographic studies of the distribution of elements in alloys and diffusion at grain boundaries are of special interest in relation to the destruction of metallic articles under various conditions [64].

The use of tagged atoms has made it possible to extend investigations of the vapor pressures of metals and alloys for studying the thermodynamic characteristics and nature of interatomic interaction in metals and alloys (the Moscow Institute of Steel, the Central Scientific Research Institute of Ferrous Metallurgy, and the Institute of Metallurgy, AN SSSR) [61, 65-67].

By the use of tagged atoms it is possible to label different cations and thus to determine transport numbers in the passage of an electric current; this greatly extends the possibilities of studying the electron structure of solids.

In the field of mechanical engineering, radioactive isotopes are used for studying friction and wear [73]. They were used to find how the rate of wear in different engine parts depends on the type of lubricant and fuel, the load and rotation speed of the shaft, and to study the mechanism of the anticorrosive action of various additives in lubricating oils, etc. [68, 69] (see Figures 2 and 3).

The use of radioactive isotopes for studying the wear of cutting tools makes it possible to decrease the amount of time and material required for determining the optimum cutting conditions [70].

Radioactive isotopes were used at the Kalinin Chemical Works for developing a technological process for the production of artificial corundum.

Radioactive isotopes have been used in studies of flotation processes [71], in investigations of the processes taking place in steam power plants [72], and in other branches of technology.

The extent of the technological investigations can be judged from the fact that over 180 papers were presented in April 1957 at the All-Union Scientific and Technical Conference on the Use of Isotopes in the National Economy and Science (Section of Technical Sciences and the Industrial Use of Isotopes) [73].

Radioactive isotopes in biology and medicine. The use of artificial radioisotopes in biology and medicine was started in the USSR in 1939 at the Gor'kii All-Union Institute of Experimental Medicine (VIEM). This work was organized jointly by two divisions of VIEM: the Division of Physiological Chemistry, and the Division of Biophysics and Photobiology. The scientists of these divisions, with the aid of the P.N. Lebedev Physical Institute AN SSSR, made the first measuring apparatus, and developed methods for the production and enrichment of phosphorus radioisotopes, and later also of bromine radioisotopes, by irradiation from radon and radium-beryllium sources. The results of the first investigations with the use of phosphorus and bromine as radioactive tracers were presented at a Conference on the Physics of the Atomic Nucleus, convened by AN SSSR in 1940 [74-76].

An investigation of phosphorus metabolism [77] was apparently the first experimental investigation with the use of radioactive isotopes in the medical and biological fields to be published in the scientific periodical press of the Soviet Union.

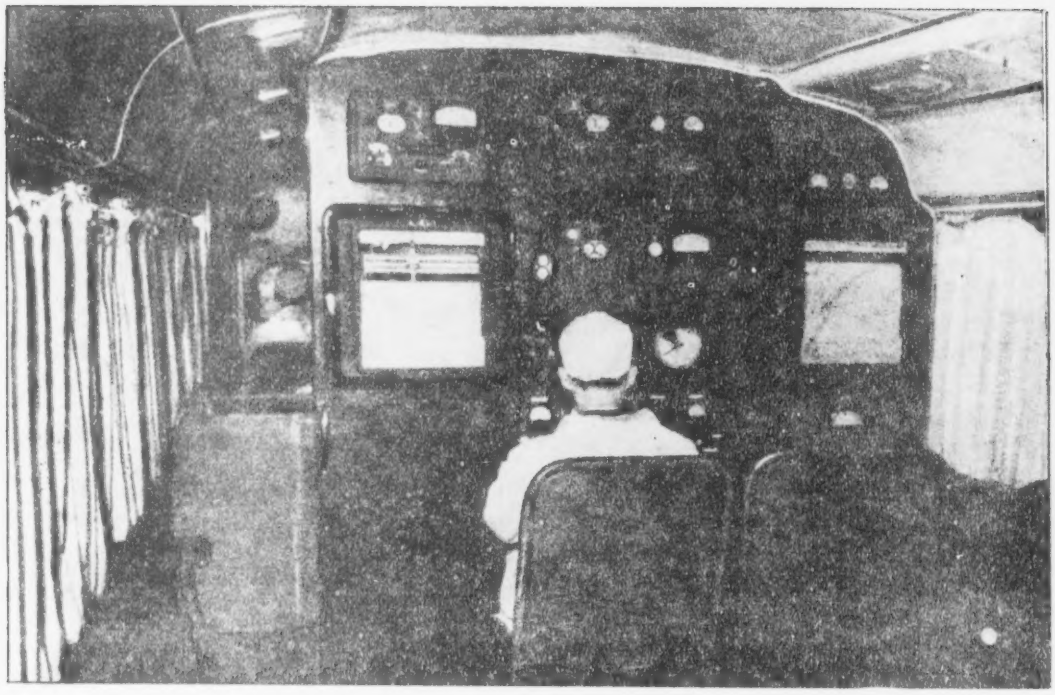

Fig. 2. Internal view of a mobile laboratory for studying engine wear by the tagged atom method.

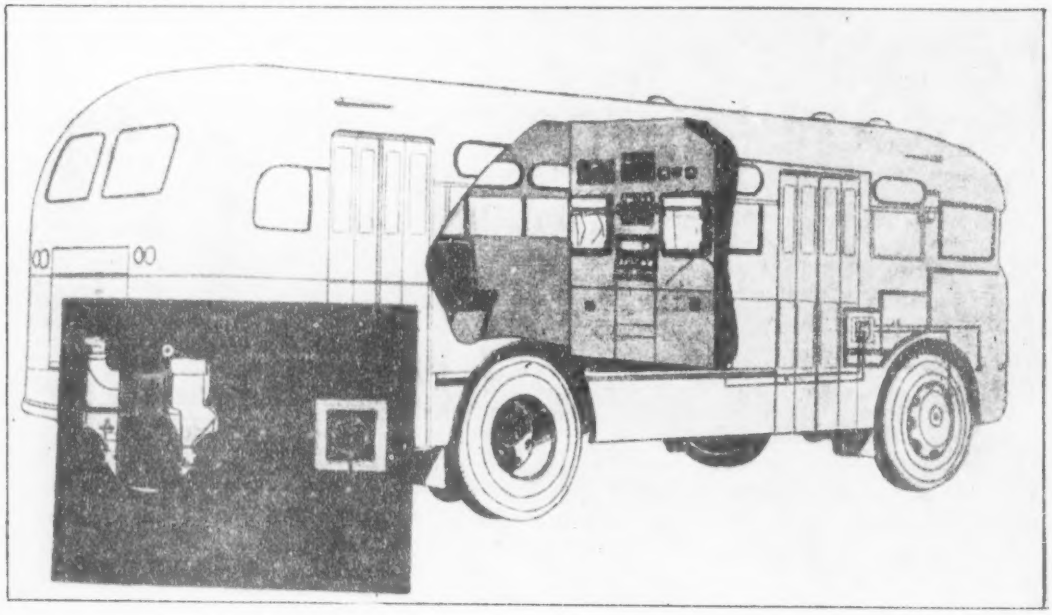

Fig. 3. External view of a mobile laboratory for studying engine wear by the tagged atom method.

During the same period an investigation was carried out in VIEM on disturbanees of the rate of inclusion of P^{32} in various organs of an animal suffering from tuberculosis [78], and disturbances of phosphorus metabolism in

the bones of an animal, damaged by tuberculosis [79]. It was found that demineralization (osteoporosis) of the affected bones is the result of an increased exchange rate in the diseased bones as compared with healthy bones, and the establishment of a low dynamic level.

At the same time, research was started in Leningrad on phosphorus metabolism in the central nervous system and on the renewal of phosphorus-containing substances in human erythrocytes. These investigations, which had a successful start, were interrupted during the war and the results were only published during the postwar period [80, 81].

During the same period E.I. Karger, who died during the war, started research on iodine metabolism in the Timiriazev Biological Institute.

In 1940 the first radioactive tracer laboratory to be set up in the medicobiological institutions of the USSR was opened in VIEM. In 1940, at the request of VIEM, the Ukrainian Physicotechnical Institute commenced the construction of a linear accelerator (deuteron gun) to be used for medicobiological research.

The successfully commenced isotopic investigations in the fields of biology and medicine were interrupted during the Patriotic War. Nevertheless, this preparatory period played an important part in their subsequent vigorous development. A circle of investigators with a mastery of the experimental techniques arose, and an even larger circle of scientific workers who were convinced, by the first attempts, of the enormous power of the isotope method for solving the most diverse problems of biology and medicine.

Immediately after the end of the war isotope research in biology and medicine began to develop at a very rapid pace, covering new problems and attracting representatives of various scientific and medical institutions, even before the mass production of isotopes by industrial methods had been organized.

One of the first postwar investigations was carried out in the Gor'kii University and the Gor'kii Medical Institute; P^{32} isotope was used to study the effects of camphor and tetramethylammonium iodide on the rate of phosphorus metabolism in the organs and tissues of rats and frogs [82]. This period was marked by the development of a number of fundamental trends in studies of biological processes. These include researches on metabolism in the central nervous system and the development of the above-mentioned work on the physiology and biochemistry of digestion, commenced before the war. They also include researches on phosphorus metabolism, particularly in muscles, protein metabolism, and bromine and iodine exchange in the organism. Work on amino acid synthesis and studies of transamination processes were carried out. Research was commenced on iodine metabolism and on development of principles of the diagnosis of thyroid disturbances with the aid of I^{131}, and on the use of isotopes in microbiology. The first steps in the use of isotopes for medical purposes were taken. The main results of these researches were summarized at the All-Union Conference on the Use of Isotopes in Biology and Medicine [83].

The contemporary period is marked by the use of isotopic tracers in practically all fields of biology and medicine.

In accordance with the traditions of Soviet biological science, such attention was devoted to studies of the functions of the central nervous system. The most significant achievement in this field is represented by the results obtained in studies of variations of the rates of metabolic processes in relation to the functional state of the central nervous system. The rates of metabolic exchange (phospholipid and protein metabolism) were shown to increase on excitation, to decrease in narcotic sleep, and to decrease still further on deep cooling of the organism. Detailed analysis of the course of renewal of the amino acid composition of the brain proteins revealed a kind of chemical topography for the rates of these processes in various sections of the central nervous system, and for different protein structures [84]. As the result of a series of investigations [85], the "circulation time" of the normal amount of phosphorus in adenosine triphosphate for different types of animals has been calculated; this is important in relation to evolutionary physiology. New views were put forward with regard to sorption bases, the so-called barrier function; particularly important data have been obtained on phospholipid metabolism, and the peculiar role of the phosphate esters of choline has been established. A lengthy series of investigations with Br^{82} [85] has been completed; its role in the activity of the nervous system has been established and the mechanisms of its physiological action studied.

In general, the use of isotopic tracers has given rise to a new field, which should be termed functional biochemistry of the nervous system, as this is the only method which makes it possible to observe the true rates of

metabolic processes and to obtain a more complete picture of their qualitative aspects. Completely new data have been obtained in studies of the digestive function, and in particular in the fields of bile formation, bile absorption, and other intimate mechanisms of these processes [86].

Tagged microorganisms were used in an extensive series of researches into questions of the pathogenesis and immunology of infections, including dysentery. Important data were obtained in this field on the distribution both of the bacterial cells themselves and of tagged "complete antigens" of dysentery bacteria in the organism. The absorption of antigens in relation to the application method, etc. has been studied. These investigations have formed the basis for the development of the special fields of isotopic bacteriochemistry and immunochemistry [83].

An extremely interesting and important field is the utilization of γ-radiation from powerful sources in the production of bacterial preparations. The possibility of sterilization of bacterial media by means of γ-radiation, and of the production of typhoid and dysentery vaccines by means of radiation inactivation has been demonstrated [85].

A series of important researches has also been carried out on the utilization of isotopes in pisciculture and animal breeding [85]. Thus, Ca^{45} was used for studying calcium metabolism in laying hens, and the very high metabolic activity of the skeletal calcium was demonstrated; S^{35} was used for studying the synthesis of wool keratin; the isotope technique made it possible to reveal and to study in detail the part played by chlorophyll in green fodder in the synthesis of hemoglobin in ruminants.

Isotopes were used in medical practice both in the development of diagnostic methods and for therapeutic purposes.

In the diagnostic use of I^{131} for determination of the functional state of the thyroid gland, original methods of using radioiodine in pathogenetic analysis were developed; in particular, a relationship between the behavior of I^{131} in the organism and the circulatory function was established [85]. Studies of this relationship in various cardiovascular diseases not only provided a firm basis for differential diagnosis of disturbances of the thyroid function, but made possible the development of an important diagnostic technique for studying circulation.

The work of Soviet investigators has provided the scientific basis for a special form of the diagnostic use of radioiodine, in which the curves representing absorption of iodine by the thyroid gland are considered not only in relation to the activity of this organ, but as a peculiar "mirror" of the functional state of the organism as a whole.

A widely developed section of the diagnostic use of isotopes is their use for studying circulation of the blood: determination of the blood flow rate with the aid of Na^{24}, of the volume of circulating blood with the aid of tagged erythrocytes, etc. The technique of resorption of sodium from intracutaneous depots in various internal diseases is worthy of attention.

The influence of γ-radiation on the permeability of the hematoencephalic and histohematic barriers to sodium phosphate has been studied [85]. The problem of the state of the histohematic barriers in relation to the clinical aspects of nervous diseases, including maxillocerebral traumas and brain tumors, has been studied in detail [85].

Different variations of methods have been proposed for studying rapid translocations of γ-emitters in the organism, in particular for studies of the circulatory function [87].

A whole series of successful attempts has been made in the utilization of isotopes in the diagnosis of cancer. Work on identification of superficially located tumors, metastases, and cancer of the uterine cervix by selective absorption of P^{32} in the tumor tissue is noteworthy. Important results have been gained by investigations of skin radiation (after introduction of P^{32}) in the region of the tumor in cancer of the mammary gland. Associated with this research are studies on the accumulation of isotopes, introduced with antitumoral sera, in tumors.

Three principal directions in the development of the therapeutic use of isotopes must be noted.

The first form of the therapeutic use of isotopes – surface application of β-emitters – is very widely used in various skin diseases, and in cases of capillary angioma it is practically the only means which gives radical results. The number of patients undergoing treatment with β-applicators runs into several thousands.

The second form is the introduction of therapeutic doses of artificial radioactive substances into the organism. The use of radioiodine for treatment of thyrotoxicoses is particularly widespread. Up to the present time, favorable results have been obtained in such treatment in over 2,500 cases in the clinics of various towns of the USSR.

This field includes the treatment of many hundreds of cases of diseases of the hematopoietic organs: erythremias and leukemias. In erythremias, internal administration of P^{32} gives lasting and stable results, while in leukemia it is possible (in conjunction with other accepted methods) to retard the course of the disease, to increase the duration of remissions, and to return the patient to working activity with a slowly developing process.

The third form is external γ-irradiation, both for treatment of surface tumors and for treatment of cancer of the internal organs. The use of Soviet γ-radiation equipment charged with Co^{60} has made it possible to provide an extensive network of cancer treatment centers with this powerful means of combating neoplasias. Research results and the enormous clinical experience which has been accumulated show that owing to the more monochromatic nature of the radiation its side effects on the skin are far less pronounced. Moreover, the possibility of charging the equipment with a considerable amount of radioactive material, of the order of 400 g-equiv Ra, which gives a powerful radiation flux, allows irradiation at much greater distances than was possible with the use of natural radium. This creates more favorable conditions for distribution of depth doses.

At the same time, most extensive use is being made of thin cobalt needles introduced into the tumor tissue, and γ-emitting cobalt applicators for irradiation of surface tumors. The results obtained by injections of colloidal Au^{198} solutions, including intraperitoneal injections, are worthy of attention [88, 89].

The therapeutic use of radioactive isotopes is so extensive in the Soviet Union that as long ago as 1954 a special scientific conference was able to summarize the results of the use of P^{32} for treatment of diseases of the hemapoietic organs and in clinical investigations. The results of investigations on the use of Co^{60} were summarized separately.

This work is not only in progress in the central institutions of Moscow and Leningrad, but is also being extensively carried on in the provinces.

Radioactive isotopes in agriculture. Isotopes are equally widely used for studying the mechanisms of the most important processes taking place in plant organisms.

For many years Baeyer's theory was accepted in plant physiology; according to this theory the primary product of photosynthesis is formaldehyde, formed by hydration of carbon. It was believed that the oxygen liberated in photosynthesis is formed from the carbon dioxide absorbed by the plant leaves from the air.

These views were refuted by the work of A.P. Vinogradov [90] with the aid of heavy oxygen. It was shown that oxygen in photosynthesis is formed from water. Numerous foreign researches, the results of which were confirmed in the USSR, proved that formaldehyde is not the primary product of photosynthesis, which is a very complex process in which phosphate esters are formed. The course of this process and the chemical composition of the products of photosynthesis depend on a number of factors, including the spectral composition of the light which induces photosynthesis [91]. In addition to carbohydrates, proteins and other compounds are formed by photosynthesis. The detailed mechanism of photosynthesis is still being studied.

The view that plants are fed by carbon dioxide from the air has also been modified and amplified by the work of A.L. Kursanov, who showed with the aid of C^{14} that plants also use carbon dioxide absorbed from the soil through the root system for photosynthesis [92]. Radioactive isotopes have been used in foliar nutrition of plants. These investigations and the researches of other workers established a close relationship between root feeding of plants and photosynthesis processes.

Studies of the mechanism of biosynthesis processes revealed the unexpected fact that chlorophyll is rapidly renewed in plant leaves [93].

Studies of the paths of formation of rubber in plants showed that rubber in kok-saghyz may be formed from carbohydrates [94]. It was shown that atoms of C^{14} from tagged sugars, acetic and levulinic acids, glycocoll, and acetoacetic acid are involved in the biosynthesis of rubber to almost equal extents, and to a much smaller extent than such atoms from alanine-2-C^{14} [95].

Many investigations have dealt with the role of radioactive radiations in the life and reproduction processes

of plants. An important paper was recently published by A.P. Vinogradov, who showed that the presence of natural K^{40} does not have any influence on metabolism in Aspergillus [96].

By means of the tagged atom method it was possible to establish the existence of metabolic exchange between stock and graft, and also between the root systems and crowns of trees. The most suitable methods for introducing fertilizers into the soil have been found by the use of fertilizers tagged with radioactive isotopes. In particular, it was shown that in the early stages of growth plants assimilate phosphorus better from small granules, whereas at later stages of growth they assimilate it better from large granules. The most suitable component ratios for organo-mineral fertilizer mixtures have been determined on the basis of these investigations [97].

The new method of "selective absorption" has provided a considerable improvement in the technique of the use of tagged atoms for studying the assimilation of fertilizers by plants. In this method, a standard tagged fertilizer is introduced into the soil together with the fertilizer under test, which is untagged. By measurement of the specific activity of the tagged element absorbed by the plant it is possible to calculate the relative assimilability of the fertilizer under test [98].

The new research technique – the use of radioactive isotopes – is being increasingly widely used by Soviet scientists and engineers in scientific research, industry, agriculture, and medicine. Evidence of the extent of such work is provided by the increasing number of papers by Soviet scientists presented at general and specialized conferences on the uses of isotopes in various branches of science and technology, which are regularly held in a number of republics of the Soviet Union and abroad.

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